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# Radioactivity
# and
# Nuclear Physics

BY

JAMES M. CORK

*Professor of Physics, University of Michigan*

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# PREFACE

The subject of Radioactivity has expanded enormously in recent years. It is undoubtedly the particular area of physics which is at present receiving most attention and which holds much promise of reward for investigations in the immediate future.

The vast quantity of information relative to the natural radioactive bodies, which was accumulated before the discovery of induced radioactivity, is still essentially valid. This material has been admirably presented in such books as that of Rutherford, Chadwick, and Ellis in the text entitled *Radiations from Radioactive Substances.*

With the discovery of "induced" radioactivity many new aspects of the subject developed. The scope of these interests varies from the simple application of radioactive tracer elements, as a tool for related sciences, to fundamental investigations dealing with the nature of the forces acting between elementary particles as revealed by "scattering" experiments.

It has been the aim in this text to offer an authentic historical development of each topic treated, and to list the pertinent references in the literature. In some cases a complete treatment would require a mathematical presentation more complicated than seemed desirable in a book of this type. It is hoped that the material presented is of such a caliber as to make the text useful as a basis for a course serving advanced undergraduates and beginning graduate students, and as a valuable aid to research workers in the subject. At the end of each chapter there is a list of problems of varying difficulty whose solution by students might aid them in gaining a working knowledge of the subject.

In addition to the original papers in the various scientific journals, many of the published texts dealing with the whole or certain particular parts of the subject have served as sources of information. Among these, in addition to the one mentioned above, it is a pleasure to refer to: F. Rasetti, *Elements of Nuclear Physics;* N. Feather, *An Introduction to Nuclear Physics;* M. Curie, *Radioactivity;* J. Hoag, *Electron and Nuclear Physics;* E. Pollard and W. Davidson, *Applied Nuclear Physics;* G. Gamow, *Atomic Nuclei;* W. Heitler, *The Quantum Theory of Radiation;* G. Hevesy and F. Paneth, *A Manual of Radioactivity;* and H. Smyth, *Atomic Energy.*

It is perhaps appropriate to express the hope that in this important field no country, either because of fear or self-complacency, will restrict for long its research program to a few favored institutions and deny the right of free investigation to the large number of independent workers who in the past have contributed so ably to the advance of the subject.

J. M. C.

*Ann Arbor, Michigan*
*September, 1946*

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## CHAPTER 1

# NATURAL RADIOACTIVITY

**1.1. The Periodic Table.** As early as 1815, W. Prout,[1] an English physician, advanced an interesting hypothesis suggesting a genetic relationship between the elements. Measurements already made at that time indicated that, if the atomic weight of hydrogen be taken as unity, then the weights of many other elements were almost, but not exactly, integral numbers. Prout suggested that these differences from whole numbers were experimental errors and that hydrogen was a mother substance out of which all other elements were built. Thus an atom of oxygen was considered as being made of sixteen atoms of hydrogen.

In 1864, J. Newlands[2] observed that, when the elements were arranged in the order of their symbol weights, the tenth was similar, chemically, to the second; the eleventh to the third, and so on. This generalization, although ridiculed when first proposed, has been termed the Newlands Law of Octaves.

In 1869, D. Mendelejeff[3] in Russia, and L. Meyer[4] in Germany, apparently independently, published almost identical tables, arranging the then-known elements in vertical and horizontal columns. The elements in any vertical column behave similarly, chemically. From left to right along a horizontal row the elements change from those with pronounced alkaline properties to those with strong acid characteristics. The properties of the elements both physical and chemical are functions

---

[1] W. Prout, Thomson, *Ann. Phil.*, **6**, 269 (1815).

[2] J. A. R. Newlands, *Chem. News*, **10**, 94 (1864).

[3] D. Mendelejeff, *Jour. Prak. Chem.*, **106**, 251 (1869).

[4] L. Meyer, *Annal. Chem. Pharm.*, **7**, 354 (1869).

TABLE 1.1. PERIODIC TABLE OF THE ELEMENTS

| | I | II | III | IV | V | VI | VII | VIII | | | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 1 H<br>HYDROGEN<br>1, 2 | | | | | | | | | | 2 He<br>HELIUM<br>3, 4 |
| II | 3 Li<br>LITHIUM<br>6, 7 | 4 Be<br>BERYLLIUM<br>9 | 5 B<br>BORON<br>10 11 | 6 C<br>CARBON<br>12 13 | 7 N<br>NITROGEN<br>14 15 | 8 O<br>OXYGEN<br>16 17 18 | 9 F<br>FLUORINE<br>19 | | | | 10 Ne<br>NEON<br>20 21 22 |
| III | 11 Na<br>SODIUM<br>23 | 12 Mg<br>MAGNESIUM<br>24 25 26 | 13 Al<br>ALUMINIUM<br>27 | 14 Si<br>SILICON<br>28 29 30 | 15 P<br>PHOSPHORUS<br>31 | 16 S<br>SULPHUR<br>32 33 34 36 | 17 Cl<br>CHLORINE<br>35 37 | | | | 18 Ar<br>ARGON<br>36 38 40 |
| IV | 19 K<br>POTASSIUM<br>39 40 41 | 20 Ca<br>CALCIUM<br>40 42 43<br>44 46 48 | 21 Sc<br>SCANDIUM<br>45 | 22 Ti<br>TITANIUM<br>46 47 48<br>49 50 | 23 V<br>VANADIUM<br>51 | 24 Cr<br>CHROMIUM<br>50 52 53 54 | 25 Mn<br>MANGANESE<br>55 | 26 Fe<br>IRON<br>54 56 57 58 | 27 Co<br>COBALT<br>(57) 59 | 28 Ni<br>NICKEL<br>58 60 61 62 64 | |
| | 29 Cu<br>COPPER<br>63 65 | 30 Zn<br>ZINC<br>64 66 67<br>68 70 | 31 Ga<br>GALLIUM<br>69 71 | 32 Ge<br>GERMANIUM<br>70 72 73<br>74 76 | 33 As<br>ARSENIC<br>75 | 34 Se<br>SELENIUM<br>74 76 77<br>78 80 82 | 35 Br<br>BROMINE<br>79 81 | | | | 36 Kr<br>KRYPTON<br>78 80 82<br>83 84 86 |
| V | 37 Rb<br>RUBIDIUM<br>85 87 | 38 Sr<br>STRONTIUM<br>84 86 87 88 | 39 Y<br>YTTRIUM<br>89 | 40 Zr<br>ZIRCONIUM<br>90 91 92 94 96 | 41 Nb<br>NIOBIUM<br>93 | 42 Mo<br>MOLYBDENUM<br>92 94 95 96<br>97 98 100 | 43 Ma<br>MASURIUM<br>96 99 101 | 44 Ru<br>RUTHENIUM<br>96 98 99<br>100 101 102 104 | 45 Rh<br>RHODIUM<br>103 | 46 Pd<br>PALLADIUM<br>102 104 105<br>106 108 110 | |
| | 47 Ag<br>SILVER<br>107 109 | 48 Cd<br>CADMIUM<br>106 108 110 111<br>112 113 114 116 | 49 In<br>INDIUM<br>113 115 | 50 Sn<br>TIN<br>112 114 115 116 117<br>118 119 120 122 124 | 51 Sb<br>ANTIMONY<br>121 123 | 52 Te<br>TELLURIUM<br>(120) 122 123 124<br>125 126 128 130 | 53 I<br>IODINE<br>127 | | | | 54 Xe<br>XENON<br>124 126 128 129 130<br>131 132 134 136 |
| VI | 55 Cs<br>CAESIUM<br>133 | 56 Ba<br>BARIUM<br>130 132 134 135<br>136 137 138 | RARE<br>EARTHS<br>See Below | 72 Hf<br>HAFNIUM<br>174 176 177<br>178 179 180 | 73 Ta<br>TANTALUM<br>181 | 74 W<br>TUNGSTEN<br>180 182 183 184 186 | 75 Re<br>RHENIUM<br>185 187 | 76 Os<br>OSMIUM<br>184 186 187 188<br>189 190 192 | 77 Ir<br>IRIDIUM<br>191 193 | 78 Pt<br>PLATINUM<br>192 194 195 196 198 | |
| | 79 Au<br>GOLD<br>197 | 80 Hg<br>MERCURY<br>196 198 199 200<br>201 202 204 | 81 Tl<br>THALLIUM<br>203 205 | 82 Pb<br>LEAD<br>204 206 207<br>208 | 83 Bi<br>BISMUTH<br>209 | 84 Po<br>POLONIUM<br>210 | 85<br>EKA IODINE<br>211 216 218 | | | | 86 Rn<br>RADON<br>222 |
| VII | 87<br>EKA CAESIUM<br>223 | 88 Ra<br>RADIUM<br>226 | 89 Ac<br>ACTINIUM<br>227 | 90 Th<br>THORIUM<br>232 | 91 Pa<br>PROTOACTINIUM<br>231 | 92 U<br>URANIUM<br>234 235 238 | 93 Np<br>NEPTUNIUM<br>238 239 | 94 Pu<br>PLUTONIUM<br>238 239 | 95 Am<br>AMERICIUM<br>241 | 96 Cm<br>CURIUM<br>241 242 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| RARE EARTHS | 57 La<br>LANTHANUM<br>139 | 58 Ce<br>CERIUM<br>136 138 140 142 | 59 Pr<br>PRASEODYMIUM<br>141 | 60 Nd<br>NEODYMIUM<br>142 143 144 145<br>146 148 150 | 61 IL<br>ILLINIUM<br>144 | 62 Sm<br>SAMARIUM<br>144 147 148 149<br>150 152 154 | 63 Eu<br>EUROPIUM<br>151 153 | 64 Gd<br>GADOLINIUM<br>152 154 155 156<br>157 158 160 |
| | 65 Tb<br>TERBIUM<br>159 | 66 Dy<br>DYSPROSIUM<br>158 160 161<br>162 163 164 | 67 Ho<br>HOLMIUM<br>165 | 68 Er<br>ERBIUM<br>162 164 166<br>167 168 170 | 69 Tm<br>THULIUM<br>169 | 70 Yb<br>YTTERBIUM<br>168 170 171 172<br>173 174 176 | 71 Lu<br>LUTECIUM<br>175 176 | |

— Radio active Isotope

of their atomic weights and many of these properties exhibit a periodic variation.

When the periodic table was first published, many spaces in it were left vacant. By 1895, sixty-five elements had been identified and classified. The elements as recognized at the present time are shown in Table 1.1. Starting with hydrogen as atomic number one and arranging elements in a numerical sequence of increasing weight, the heaviest element is atomic number 96, called curium, and every intervening number is represented by an element. The position of the element in this sequence is termed its atomic number. It will be seen that this number represents the number of negative electrons in the outer orbits of the atom and hence also the number of positive charges in its nucleus. It thus determines the chemical behavior of the element. The four heaviest elements, whose atomic numbers are 93, 94, 95, and 96, have been made from uranium by induced nuclear transmutations.[5]

For each atomic number or element there may be atoms having one or more different atomic weights. These various atomic weights are termed isotopes, and for any element they differ among themselves approximately by small integral numbers of mass units. The isotopes for a given element always occur with a fixed relative abundance.

**1.2. Atomic Weights, the Chemical and the Physical Scale.** A scale of atomic weight measurement has been developed based upon the relative combining weights of the elements in chemical reactions. In this scale, oxygen is taken as a standard, with an assigned value of exactly 16.00. The corresponding value for hydrogen is 1.00785.

Studies in band spectra indicated that oxygen did not consist of a single isotope, as had at first been suspected.[6] A careful investigation with the mass spectrograph confirmed the prediction that, in addition to the isotopes of mass 16, there were also traces of isotopes of masses 17 and 18. Now, if it be assumed that the mass of the abundant isotope of oxygen is exactly 16, then isotope 17 was found[7] to have a mass of 17.0045 and an abundance of 0.04%; and isotope 18, a mass number of 18.0037 and an abundance of 0.20%. On averaging these quantities, a value for the atomic weight of oxygen, on what is termed a "physical" scale, is $16.00435_7 \pm 0.00008_6$. It thus follows that the atomic weights on the physical scale[8] are in the ratio of 1.000272 to 1, to the corresponding weights on the chemical scale.

---

[5] G. T. Seaborg and J. G. Hamilton, *Science*, 102, 556 (1945); *Chem. and Eng. News*, 23, 2190 (1945).

[6] W. F. Giauque and H. L. Johnston, *Jour. Amer. Chem. Soc.*, 51, 1436, 3528 (1929).

**1.3. Isotopes and Packing Fraction.** With the precision now attainable in mass spectroscopy, it is possible to express the mass of an isotope to about six significant figures. Similarly, the relative abundance of the isotopes comprising an element has been accurately determined. No variation in this observed abundance ratio has ever been found for any of the natural elements regardless of the geographical derivation of the source, except for those elements associated with radioactivity.

The interesting observation has been made by Aston that elements of odd atomic number have only one or two components, whereas elements of even atomic number may have several, in some cases as many as eleven isotopes. This fact is illustrated by Figure 1.1, which represents the isotopic distribution in the odd-numbered element manganese (25) and the even-numbered element tin (50).

On the mass scale in which 16.0000 represents the abundant isotope of oxygen, the mass of the abundant isotope of hydrogen is 1.00813, and of helium, 4.00388; and of the neutron, the mass is 1.00893. Now, it is clear that if the heavier elements be regarded as constructed from the lighter components, the masses do not seem correct. For example, two neutrons plus two hydrogen atoms have a mass of 4.03412 instead of 4.00388, as is found for helium 4. This apparent loss in mass of 0.03024 mass units is extremely important in determining the relative stability of the element and the energy exchange in nuclear reactions. Similarly, for oxygen, eight hydrogen atoms plus eight neutrons might be expected to have a mass of 16.13648 instead of 16.0000, i.e., a mass loss of 0.13648. The mass loss per particle in the packing or build-up of the oxygen nucleus is then one-sixteenth of this value, or 0.00853. This quantity is called a "packing fraction." If oxygen be taken as a reference element, with zero value, then a table can be constructed showing the packing fractions for all of the other elements. The numbers are usually expressed in ten-thousandths of a mass number so that the hydrogen-neutron value would be plus 85.3. Such a packing-fraction curve, including all the elements on which measurements had been made, was computed by Aston and is shown in Figure 1.2. Those elements lying at the minimum of the curve might be regarded as most stable because, in their formation, the fundamental particles have given up a maximum portion of their mass.

---

[7] J. Mattauch, *Phys. Rev.*, **50**, 617, 1089 (1936); B. F. Murphy, *ibid.*, **59**, 320 (1941).

[8] R. T. Birge, *Phys. Rev.*, **13**, 233 (1941).

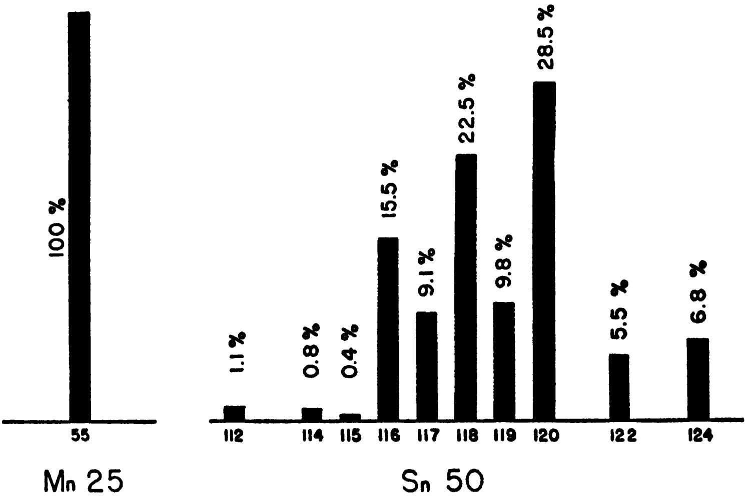

FIG. 1.1. Isotopic distribution in manganese and tin.

The packing fraction for an element of atomic weight $A$, consisting of $N$ protons plus neutrons is thus given as:

$$(\text{P.F.}) = \frac{A - N}{N} \times 10^4.$$

**1.4. Abundance and Properties of Uranium and Thorium.** Because the subject of radioactivity owes its origin to uranium and thorium, and because of the very important role these elements are certain to play in the future world economy and world peace on account of nuclear fission, it is of interest to know something of their abundance and distribution. Uranium was first discovered in 1789 by Klaproth, and in 1841 the metal was first prepared by Peligot, by the reduction of uranous chloride ($UCl_4$). The metal has a specific gravity of 18.7, an atomic weight of 238.07, a melting point of 1150° C., and atomic number 92. Thorium was discovered by Berzelius in 1828. The metal has a specific gravity of 11.2, an atomic weight of 232.12, a melting point of 1845° C., and atomic number 90.

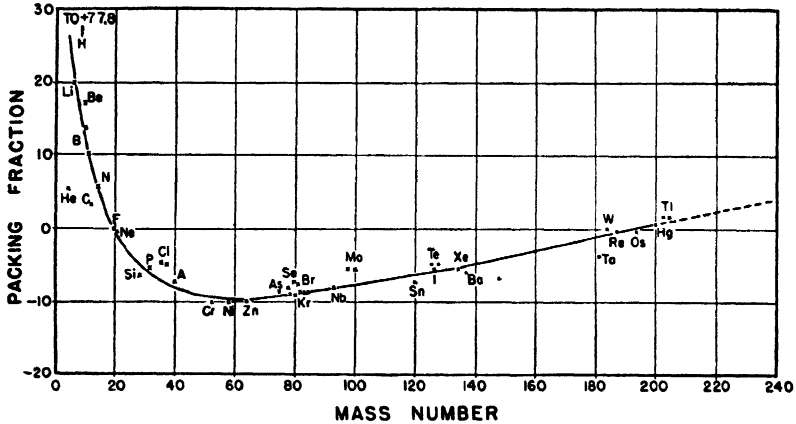

Fig. 1.2. Packing fractions for the elements.

It has been estimated that uranium is present in the earth's crust up to about four parts in a million, while thorium is about three times as abundant. Natural deposits of both elements are distributed widely over the earth's surface. The most common natural form of uranium is pitchblende, which is really an oxide of uranium, $U(UO_4)_2$. This ore is usually found in pockets or veins in sedimentary rock. Rich deposits occur in Czechoslovakia, the Belgian Congo, Cornwall, and most abundant of all in the Great Bear Lake region in Canada. Carnotite is a yellow crystalline powder consisting of a vanadate with uranium, sometimes up to 50%. Fairly large deposits are found in Colorado and in North Carolina.

Thorium is often found associated with the rare earth elements. Monazite is a cerium phosphate, $CePO_4$, containing up to 10% thorium and about 1% uranium. It is found in India, Brazil and the United States. Chalcolite, a green crystal, is a phosphate of copper and uranium, sometimes up to 50%, and is found in Portugal and England. Orangite, thorite, and soddite are silicates rich in thorium, found in Norway and in the Belgian Congo. Thorianite is an oxide consisting of about 65% thorium and about 10% uranium and is found in Ceylon. Samarskite is a tantalate of rare earths, particularly yttrium, containing up to 15% uranium and 4% thorium. It is found in Russia, India, Madagascar, and the United States.

It is apparent that no important nation is without a supply of this crucial material.

**1.5. Discovery of Radioactivity.** While studying the phosphorescence of various materials in 1896, Henri Becquerel[9] was led to the discovery of radioactivity. He noticed that from several uranium salts an invisible radiation was emitted, capable of traversing thin layers of opaque materials and affecting a photographic plate. After a lapse of several months, during which time the uranium salts were kept in complete darkness with no apparent diminution in their ability to activate photographic emulsions, Becquerel concluded that the radiation was not phosphorescent, that is, it was not dependent upon any primary exciting radiation. It was also observed that the air close to the uranium salts was electrically conducting so that a charged electroscope could be discharged.

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[9] H. Becquerel, *Comptes Rendus*, **122**, 501, 689 (1896); et seq.

In 1898, G. C. Schmidt[10] and Mme. Curie[11] independently observed that similar radiations were emitted by compounds of thorium. Madame Curie noted further that cerium, niobium, and tantalum gave similar slight activities and that yellow phosphorus was very active, whereas red phosphorus was not. These mistaken conclusions were made because only the apparent ionizing property of the substances was observed, and humidity changes in the electroscope produced a similar effect.

Madame Curie noted that natural pitchblende $U(UO_4)_2$ was more active than pure uranium oxide and that natural chalcolite $(Cu + U)SO_4$ was more active than the same substance when prepared in the laboratory. She made a further careful check on the radioactivity from various compounds of uranium and thorium and found that the activity was proportional solely to the amounts of uranium or thorium present regardless of their state of chemical combination. Thus she decided that the radioactivity must be an atomic phenomenon. These observations led to a tireless search for the source of the increased activity in the natural ores. As a result it was found possible to isolate from the pitchblende a sulphide of bismuth having an activity four hundred times greater than that from the same quantity of uranium. Pure bismuth sulphide was shown to be completely inactive. It was therefore assumed that a new element was present with the bismuth. This element was called polonium.[12]

From another portion of the pitchblende residue it was found that an exceedingly active barium chloride could be fractionally precipitated. The atomic weight of barium in this separation was noted to be greater than the usual value. With this precipitate it was possible to darken a photographic plate in one-half minute, whereas several hours would have been required by the same amount of any other compound of thorium or uranium. It was therefore assumed that another new element was present, associated with the barium. This element was called "radium,"[13] from the Latin *radius*, meaning ray.

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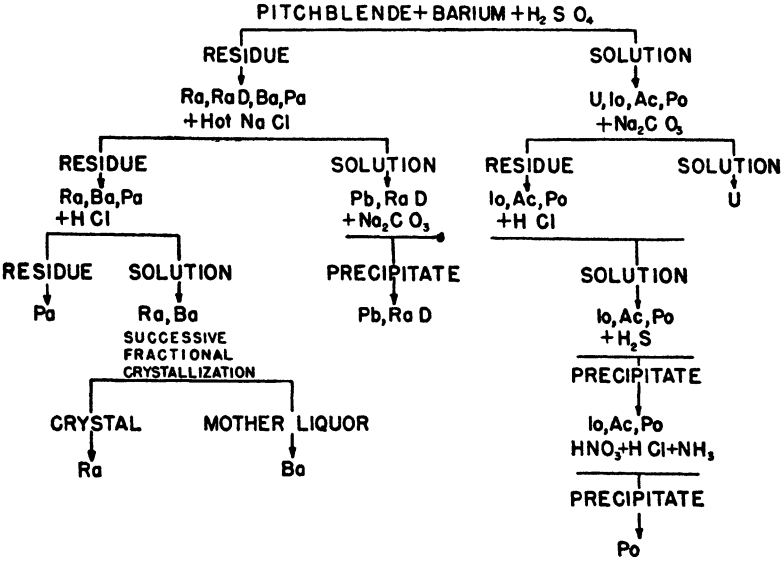
[10] G. C. Schmidt, *Annal. Phys. Chem.*, 65.1, 141 (1898).

[11] Mme. Sklodowska-Curie, *Comptes Rendus*, 126, 1101 (1898).

[12] P. Curie and M. Sklodowska-Curie, *Comptes Rendus*, 127, 175 (1898).

**1.6. The Chemical Separation of Radium.** Pitchblende from St. Joachimsthal, Czechoslovakia, served as the source for the first polonium and radium isolated by Pierre and Marie Curie. In this deposit the ore is associated with dolomite and quartz at a depth of about 1500 feet. The phases of extraction are shown schematically in Table 1.2.

TABLE 1.2. THE SCHEMATIC SEPARATION OF RADIUM AND POLONIUM FROM PITCHBLENDE



Barium was added as a carrier for the radium, and the pitchblende was dissolved in sulphuric acid. The radium followed the separated residue which after purification was converted to a chloride or a bromide solution. After purification this was subjected to successive fractional crystallizations to separate the barium from the radium. This latter operation as first carried out was exceedingly tedious and involved scores of successive crystallizations, each time leading to a crystal richer in radium, until the final crystal was regarded as sufficiently pure.

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[13] P. Curie, Mme. P. Curie, and G. Bémont, *Comptes Rendus*, **127**, 1215 (1898).

In recent years the major part of the world's supply of radium has come from the Great Bear Lake region in Canada. Each gram of aged uranium contains about $3.4 \times 10^{-7}$ grams of radium. From an annual production of about 400 tons of the concentrated uraninite ore, which is principally an oxide of uranium, 80 to 90 grams of radium have been recovered. Until very recently the rejected uranium had little value except for its application in the ceramic and glass industries, where it was used for its ability to induce a certain coloration. The current prices of these products are about $2.00 per pound for uranium oxide, about $20.00 per pound for pure uranium metal, and about $25,000 per gram for radium.

**1.7. Properties of the Radiation.** In announcing the discovery of X-rays in 1896, W. Roentgen reported quite completely and accurately on their properties. On the other hand, the properties of the radiation emitted by uranium and its compounds were not at first correctly recognized. It was rightly concluded that this radiation rendered gases electrically conducting and that it would traverse layers of opaque materials. It was, however, incorrectly concluded that the radiation could be reflected by a mirror and refracted in a glass prism in the same way as ordinary light. It was further reported that when identical radiations were passed through two plates of tourmaline, in one case with axes parallel and in another case with axes at right angles, extinction occurred in the latter case and not in the former, just as for ordinary light. The radiation was also incorrectly reported to be strengthened when the uranium was exposed to an electric arc.

Becquerel was not alone in making observations which had later to be corrected. Two years later, G. Schmidt, in announcing the discovery of the radiation from thorium, asserted that the radiation was refracted by a glass prism in the same manner as ordinary light.

In 1899, it was shown independently by Giesel[14] and by S. Meyer and von Schweidler[15] that the radiation could in part be deflected and resolved by the application of a strong perpendicular magnetic field. P. Villard showed that the portion of the radiation not deflected by the magnetic field would in part traverse thick layers of matter.[16] The deflected part of the radiation behaved like electrons and was termed *beta radiation*. The entire remaining undeflected part was at first termed *alpha radiation*. In 1903, Rutherford showed that if the magnetic field was sufficiently strong the alpha radiation also could be deflected, behaving as if positively charged.[17] R. Strutt found that a component of the radiation was highly penetrating and was undeflected even in the strongest electric or magnetic fields.[18] This component was termed *gamma radiation* and was believed to be similar in nature to X-rays.

The resolution of these three radiations emanating from a specimen of radium placed at the bottom of a small drill hole in a lead block is shown in Figure 1.3. In this figure the magnetic field is directed out of the paper, and the beta particles, being negatively charged and of small mass, are strongly deflected to the left. The alpha rays were ultimately shown to consist of the nuclei of helium atoms stripped of their outer electrons and hence positively charged. The undeviated beam is electromagnetic radiation of extremely short wavelength. Substances that emit any of these radiations are said to be "radioactive," and the science dealing with all phases of the phenomenon is termed "radioactivity."

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[14] F. O. Giesel, *Ann. Phys. Chem.*, **69,** 834 (1899).

[15] S. Meyer and E. von Schweidler, *Phys. Zeits.*, **1,** 90 (1899).

[16] P. Villard, *Comptes Rendus*, **130,** 1178 (1900).

[17] E. Rutherford, *Phil. Mag.*, **5,** 177 (1903).

[18] R. J. Strutt, *Proc. Roy. Soc.*, **72,** 208 (1903).

In summarizing, the radiations from a fairly strong sample of radium may:

*a.* Render gases conducting, as shown by the ability to discharge a charged electroscope,

*b.* Cause materials to fluoresce, particularly those commonly used with X-rays, such as platino-barium cyanide, zinc sulphide, and calcium tungstate,

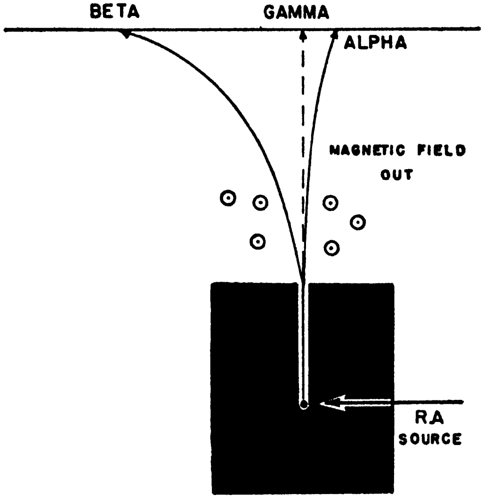

Fig. 1.3. Resolution of the radiation from a radium source.

*c.* Affect photographic plates, as does ordinary light,

*d.* Traverse material layers, opaque to ordinary light,

*e.* Develop heat continuously in any matter absorbing the radiation,

*f.* Produce helium in the containing tube in an amount increasing directly with the time,

*g.* Develop helium outside the gas-tight container, if the walls are very thin,

*h.* Develop another heavy gas, radon, within the sealed container in amounts proportional to the time. This gas when isolated is also found to emit radiation and ultimately vanish leaving a lead-like deposit, and

*i.* Kill any living organism on exposure, if intensity is sufficient.

**1.8. Atomic Disintegration.** Until 1902, studies had been confined to the properties of the radiation and to the discovery of new sources. It was, however, generally thought that the radiation was an invisible fluorescence due to some unidentified primary excitation. It was subsequently noted that any substance, kept in the proximity of a radioactive body for some time, became radioactive. This induced radioactivity could be modified by subjecting the material to heating or by placing it in a vacuum. In 1903, Rutherford and Soddy demonstrated that the induced radioactivity was really due to a gas arising in the original radioactive body as a consequence of its radioactivity and diffusing away into its surroundings. On passing the gas through tubes immersed in liquid air this emanation from thorium condensed at a temperature of −120° C., and the corresponding emanation from radium at −150° C.

It became increasingly clear as numerous natural radioactive bodies were isolated that certain genetic relationships existed between them. Thus for the first time evidence was at hand that the atoms of an element, which from their very name were regarded as indivisible, must, in the radioactive process, disintegrate. Every uranium atom could in succession eject several light particles, each time leaving a new residual atom.

**1.9. The Fundamental Particles.** If by "fundamental particle" is meant an elementary unit that under no condition can be transformed into one or more other particles, then no fundamental particle exists. At various times it has seemed certain that such entities as protons and electrons might be so regarded. On further investigation it must be concluded that within a nucleus or on suitable collision, protons transform into other particles, and electrons form from and convert into photons. There are certain elementary particles, however, which although transmutable among themselves, seem to serve as the building units for more complicated matter.

These particles are shown collectively in Table 1.3, and are as follows:

*a. Electrons*—Electrons are particles whose electric charge is indivisible and of value $-4.8021 \times 10^{-10}$ electrostatic units. At small velocities they possess a mass which expressed in mass units is 0.00054862 and in grams is $9.19 \times 10^{-28}$. The term "electron" with the interpretation now accepted, was first used by Stoney.[19] Credit for proof of the existence of these particles is usually given to J. J. Thomson.[20] Streams of the particles in motion in a discharge tube are called cathode rays. When ejected from a radioactive body they are termed beta rays. As the velocity ($v$) of the electrons increases so as to approach the velocity of light ($c$), $3 \times 10^{10}$ cms per second, the mass ($m$) of the electrons increases above their mass ($m_o$) at slow velocities according to the equation

$$m = \frac{m_o}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \tag{1.1}$$

This change in mass with velocity was first experimentally demonstrated by W. Kaufmann in 1902.[21]

*b. Protons*—Protons are the positively charged nuclei of hydrogen atoms that have been stripped of their orbital electrons. Since each complete hydrogen atom is electrically neutral and possesses a single orbital negative electron, then the electric charge of the nucleus is positive and equal in magnitude to the electron. Protons were first observed as positive "canal" rays in a discharge tube, in 1886 by Goldstein.[22] Twelve years later, W. Wien [23] determined the ratio of their charge $e$ to their mass

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[19] G. J. Stoney, *Sci. Trans. Roy. Soc.*, Dublin, **4**, 563 (1891).

[20] J. J. Thomson, *Phil. Mag.*, **44**, 293 (1897).

[21] W. Kaufmann, *Nach. Math. Phys. Klass*, **5**, 219, 296 (1902).

[22] E. Goldstein, *Berl. Ber.*, **39**, 691 (1886).

[23] W. Wien, *Berl. Phys. Gesell. Verh.*, **16**, 165 (1897); **17**, 10 (1898); *Wied. Annal.*, **65** **440** (1898).

$m$. The value of $e/m$, although highly inaccurate, was found to be the same regardless of the kind of gas in the discharge tube and was very small compared to the value of $e/m$ found by J. J. Thomson for electrons. In a more accurate study of the canal rays, Thomson[24] noted that he sometimes observed a value of the order of 10,000 electromagnetic units per gram which was considerably larger than the value reported by Wien. At other times he found a value only half as large and, with helium gas in the tube, a value only one-fourth as large. This was interpreted as meaning that in the stream of canal particles both atomic and molecular hydrogen ions were present. The molecule of double mass had lost only one electron. Similarly the helium atom had lost only one electron. The mass number of the proton, based on the oxygen scale, $m = 16.0000$, is 1.007582, which represents $1.67248 \times 10^{-24}$ grams. For the neutral hydrogen atom the mass number is 1.00813 and the mass is $1.67339 \times 10^{-24}$ grams.

TABLE 1.3. THE FUNDAMENTAL PARTICLES

| ELECTRIC CHARGE | | | MASS | |
|---|---|---|---|---|
| + | NEUTRAL | — | UNITS | GRAMS |
| PROTON<br>W. Wien (1898)<br>J.J. Thomson (1906) | NEUTRON<br>J. Chadwick (1932)<br>I. Curie F. Joliot | | $M_p$ 1.00758<br>$M_n$ 1.00893 | $1.66 \times 10^{-24}$ |
| MESON<br>(MESOTRON) | | MESON<br>C. Anderson and S. Neddermeyer (1936) | $\sim 0.11$ | $18 \times 10^{-26}$ |
| POSITRON<br>C. Anderson (1932) | NEUTRINO<br>NO DIRECT EVIDENCE | ELECTRON<br>J.J. Thomson (1897) | 0.000548 | $9.19 \times 10^{-28}$ |
| | PHOTON<br>A. Einstein (1905)<br>X Rays, Gamma Rays | | 1 M.E.V.<br>$= 0.00107$ | $1.762 \times 10^{-27}$ |

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[24] J. J. Thomson, *Phil. Mag.* VI, 13, 561 (1907).

*c. Neutrons*—Neutrons are particles whose mass is only slightly greater than that of the hydrogen atom and whose electric charge is zero. Their discovery is attributed to Chadwick [25] in 1932, although it might be claimed that his disclosure was possible only because of the investigations of W. Bothe and H. Becker [26] and of I. Curie-Joliot [27] and F. Joliot.[28] These experiments will be described later. The neutron has no orbital electrons and, being uncharged, it is influenced by other atoms only at very close range. Consequently it will traverse thick layers of heavy elements with little loss in energy. This lack of charge also makes it difficult to detect the neutron by any direct method. The mass number of the neutron is 1.00893, which is equivalent to $1.67472 \times 10^{-24}$ grams.

*d. Positrons*—Positrons are particles exactly like electrons in mass and magnitude of electric charge but which differ in that their charge is positive in sign. In making cosmic ray studies in 1932 with a vertical Wilson cloud chamber provided with a strong magnetic field, C. D. Anderson [29] noticed certain tracks whose curvature was in a direction opposite to that of the usual electrons. This could conceivably occur by the reflection of negative electrons (see Figure 5.4*A*). Excluding this possibility, the conclusion could be drawn that the paths were those of positively charged particles. They were at first thought to be protons but on further investigation Anderson announced [30] them to be positive electrons or "positrons." In nuclear reactions, to be described later, these particles are very commonly emitted. Their life span is short, lasting only during their transit which is usually less than a micro-second. In their absorption in matter they behave [31] quantitatively like negative electrons.

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[25] J. Chadwick, *Nature,* **129,** 312 (1932).
[26] W. Bothe and H. Becker, *Zeits. f. Phys.,* **66,** 289 (1930).
[27] I. Curie-Joliot, *Comptes Rendus,* **193,** 1412 (1931).
[28] F. Joliot, *Comptes Rendus,* **193,** 1415 (1931).
[29] R. A. Millikan and C. D. Anderson, *Phys. Rev.,* **40,** 325 (1932).
[30] C. D. Anderson, *Phys. Rev.,* **43,** 491 (1933).
[31] B. R. Curtis, *Phys. Rev.,* **53,** 986 (1938).

*e. Neutrinos*—Studies of the energy distribution of the beta radiation emitted by a radioactive substance showed it to be continuous. This result presented certain fundamental difficulties. Most evidence indicated the existence of definite energy states within the nucleus, hence any emission should have involved definite discrete energies, instead of a continuous distribution. The interpretation seemed to offer only two alternatives. These were, namely, to relinquish the principle of "conservation of energy" as applied to intranuclear processes or to postulate the existence of a nondetectable, yet energetic, particle which is emitted with each beta particle, so that the sum of the two energies is a constant. This particle is assumed to have a mass perhaps smaller than that of the electron and no electric charge. Hence it would be extremely difficult to observe. Many experiments of an indirect nature have been attempted to prove the existence of the neutrinos. One of these was a calorimetric experiment by Ellis and Wooster to be described later.[32]

A nucleus that emits a beta particle and a neutrino would recoil with a momentum equal to that of the sum of the momenta of the two particles, even though one of them cannot be seen. To this end, Crane and Halpern [33] observed the paths of recoiling, gaseous, radioactive chlorine atoms in a Wilson cloud chamber. By counting the number of droplets formed along the path, they could compute the energy and hence the momentum of the particle. Their conclusion favored the existence of the neutrino but was not absolute proof of its existence. Results of a similar nature were found by Allen, using a somewhat different experimental arrangement.[34]

*f. Mesons*—In 1935, H. Yukawa [35] presented a theoretical discussion of the short-range forces acting between a neutron and a proton in the nucleus. In accounting for beta disintegration he was led to a prediction of the existence of quanta of mass about one-tenth that of the proton.

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[32] C. D. Ellis and W. A. Wooster, *Proc. Roy. Soc. A*, **117**, 109 (1927).

[33] H. R. Crane and J. Halpern, *Phys. Rev.*, **53**, 789 (1938).

[34] J. S. Allen, *Phys. Rev.*, **61**, 692 (1942).

[35] H. Yukawa, *Proc. Phys.-Math. Soc.*, Japan, **17**, 48 (1935).

In 1936, Anderson and Neddermeyer observed [36] among their many cloud chamber tracks several traces of particles whose penetrating powers were much greater than would have been indicated by their radii of curvature, had they been electrons. Many subsequent investigations [37] studying these particles near the end of their range showed them to have varying masses averaging about two hundred times that of the electron. They may be either positive or negative in sign with a charge equivalent to that of the electron. They are short-lived, probably changing into ordinary electrons and neutrinos.

*g. Photons*—Electromagnetic radiation in many ways displays a corpuscular nature. In 1905, Einstein [38] proposed the now famous photoelectric equation

$$h\nu = \tfrac{1}{2}mv^2 + P \tag{1.2}$$

The product of the Planck constant $h$ and the frequency $\nu$ represents the energy of the incident photon, and $\frac{1}{2}mv^2$ is the kinetic energy of the escaping electron which required an energy $P$ to release it from the surface. Einstein later formulated this postulate as: "Every quantity of energy of any form whatever represents a mass which is equal to this same energy divided by $C^2$, where $C$ is the velocity of light, and every quantity of energy in motion represents momentum."

It was seven years later before this relationship was experimentally verified.[39] In nuclear reactions the photons or gamma rays may possess very large energies. On occasion they are found in their passage through matter to disappear entirely. On their death they give rise to an electron pair, that is, both a positive and a negative electron. It is therefore reasonable to include photons as fundamental particles.

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[36] C. D. Anderson and S. Neddermeyer, *Phys. Rev.*, **50**, 263 (1936).

[37] J. C. Street and E. Stevenson, *Phys. Rev.*, **52**, 1003 (1937); A. Ruhlig and H. R. Crane, *Phys. Rev.*, **53**, 266 (1938); and E. J. Williams and E. Pickup, *Nature*, **141**, 685 (1938).

[38] A. Einstein, *Ann. d. Phys.*, **17**, 132 (1905).

[39] K. T. Compton, *Phil. Mag.*, **23**, 579 (1912); A. L. Hughes, *Phil. Trans. Roy. Soc.*, **212**, 205 (1912); R. A. Millikan and J. R. Wright, *Phys. Rev.*, **36**, 68 (1912).

**1.10. The Decay Constant and Half-life.** In 1900, from a solution of uranium, Crookes [40] precipitated a carbonate which, although free from uranium, possessed an activity many times as great. At the same time the residual uranium solution lost its ability to affect a photographic plate. A similar separation was carried out on thorium by Rutherford and Soddy.[41] Because of their unknown character, the active substances thus separated were called uranium X and thorium X, respectively. The strong initial activity of these separated substances was found to decrease rapidly, while at the same time the parent substances appeared to regain their original activity. These changes, with time as noted by Rutherford for both uranium and thorium, are shown in Figure 1.4. The form of the decay

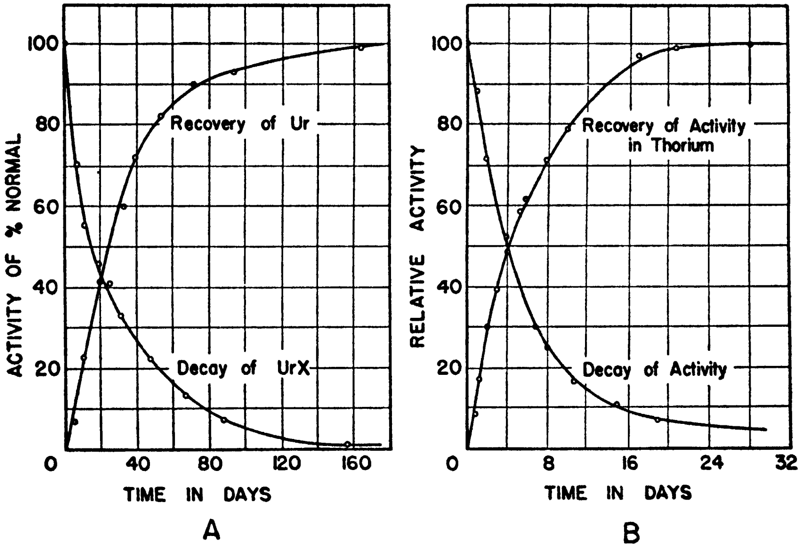

FIG. 1.4. The decay of uranium X and thorium X and the recovery of the parent materials.

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[40] W. Crookes, *Proc. Roy. Soc.*, 66, 409 (1900).

[41] E. Rutherford and F. Soddy, *Phil. Mag.*, 5, 445, 576 (1903).

curves suggested a logarithmic decrease of the number of active particles. This follows the assumption that the number of particles $\Delta N$ disintegrated in a time $\Delta t$, is proportional to the total number of active particles $N$ and the time $\Delta t$ and to a probability constant $\lambda$ defined by the equation

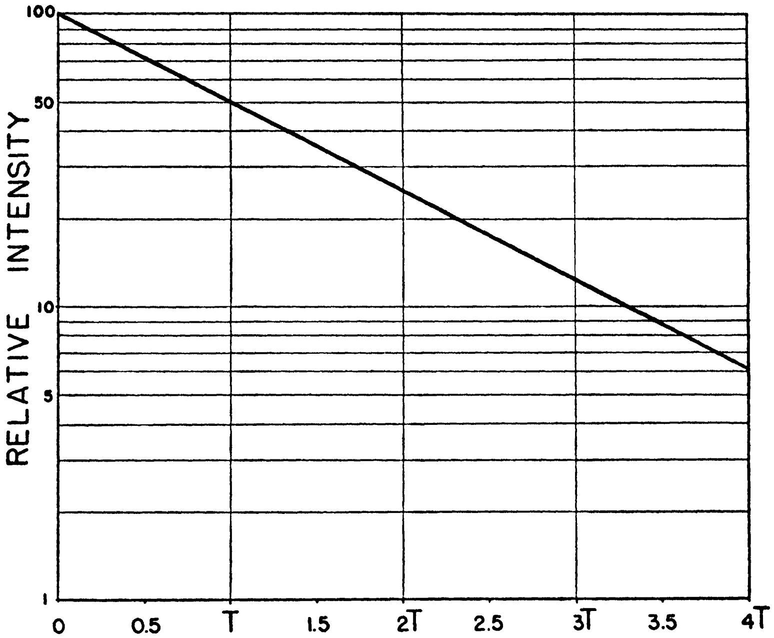

Fig. 1.5. The logarithmic decay of radioactive source.

$$\Delta N = -\lambda N \Delta t \tag{1.3}$$

It is evident that $\lambda$ may then be defined as the relative number of particles disintegrating per second, and has the dimensions of reciprocal seconds. By assuming an initial number $N_o$ at $t = 0$, then on integration of equation 1.3 it follows that the number $N$ of particles remaining after the lapse of time $t$ is

$$N = N_o e^{-\lambda t} \tag{1.4}$$

Now if $\frac{N}{N_o}$ be set equal to $\frac{1}{2}$, then on taking logarithms it follows that

$$\log_e 2 = \lambda t = 0.693 \tag{1.5}$$

so that the half-life, $T_{\frac{1}{2}} = \frac{0.693}{\lambda}$ seconds. This quantity is very generally used in describing radioactive emitters. From equation 1.4 it follows that if the intensity of any radioactive source of single valued half-life be plotted logarithmically against the time, then a straight line of negative slope results, as shown in Figure 1.5. If a radioactive source emits radiations decaying according to several different half-lives, then the analysis may be carried out from such a semi-logarithmic plot by subtracting in succession the straight line plot for the longest half-life remaining. An example of this kind is shown in Figure 1.6, representing a certain radioactive indium consisting of three activities having half-lives of 54 minutes, 72 seconds and 13 seconds. On subtracting the straight line rep-

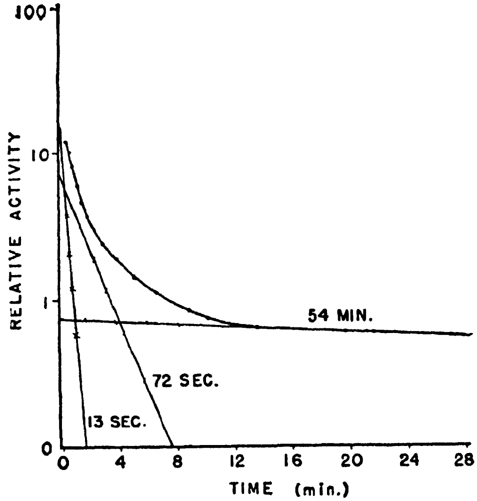

FIG. 1.6. The analysis of a composite decay curve into its three components.

resenting the 54-minute activity, a residual curve having a straight end segment results. This represents the 72-second activity, and after its subtraction a single straight line remains for the 13-second activity.

The activity along the recovery curve in Figure 1.4 is more complicated. Starting with $N_U$ uranium atoms with a disintegration constant $\lambda_U$, then the loss per second is

$$\frac{dN_U}{dt} = -\lambda_U N_U \tag{1.6}$$

This loss of uranium atoms represents a corresponding gain in the daughter substance $A$, which in turn loses a number $\lambda_A N_A$ per second so that the net change per second in $A$ is

$$\frac{dN_A}{dt} = +\lambda_U N_U - \lambda_A N_A \tag{1.7}$$

A solution of equations 1.6 and 1.7 gives for the number $N_A$ at any time $t$

$$N_A = \frac{\lambda_U N_U}{\lambda_A - \lambda_U} [e^{-\lambda_U t} - e^{-\lambda_A t}] \tag{1.8}$$

The disintegration constant $\lambda_U$ is very small compared to $\lambda_A$ and after a sufficiently long time $t$, $e^{-\lambda_A t}$ becomes equal to zero. Assuming that the change in $N_U$ is negligible, then equation 1.8 may be transformed to read

$$\frac{N_A}{N_U} = \frac{\lambda_U}{\lambda_A} = \frac{T_{½}(A)}{T_{½}(U)} \tag{1.9}$$

This means that the daughter substance is in equilibrium with the parent and the numbers of particles of the two substances are in the same ratio as their half-lives. Much use will be made of this fact in later discussions.

The reciprocal of $\lambda$ is the time required for the intensity to drop to $\frac{1}{e}$ or $\frac{1}{2.7}$ of its initial activity. This time may be shown to be the "mean-life" for the initial particles. Its relationship to the half-life for any emitter is shown in Figure 1.7.

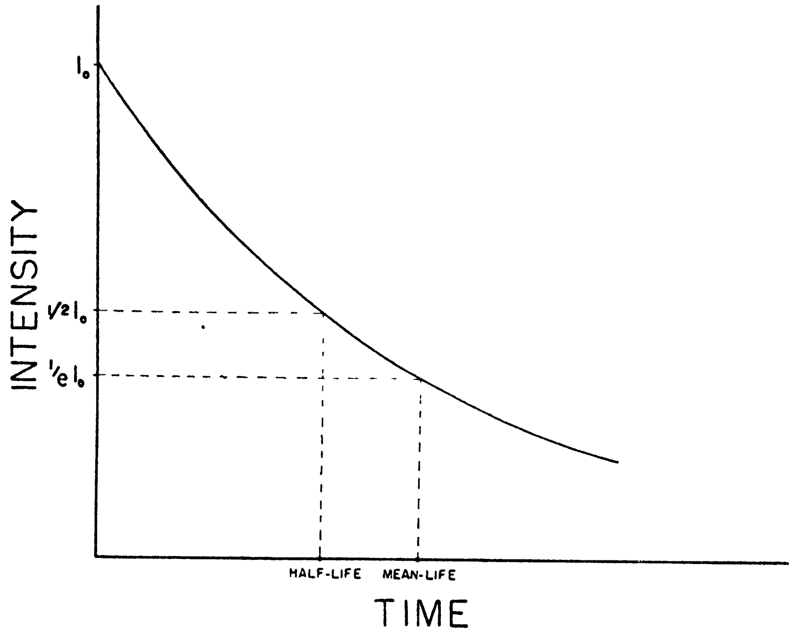

FIG. 1.7. Showing relation between half-life and mean-life.

**1.11. The Uranium-Radium Family.** Following the discovery of polonium and of radium in 1898 and the notion of atomic disintegration, numerous other radioactive bodies were isolated and identified. Each substance was characterized by a particular half-life and the emission of a particular type of radiation, with definite energy limitations. Among these may be mentioned the discovery of actinium in 1900 by Debierne;[42] of radio-lead by Hofmann in 1904;[43] and of ionium, the direct parent of radium, by Boltwood in 1907.[44]

Uranium exists in nature in the form of three semistable isotopes of mass 234, 235, and 238; in relative abundance 0.006%,

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[42] A. Debierne, *Comptes Rendus*, 130, 906 (1900).
[43] K. Hofmann, L. Gonder, and V. Wolf, *Ann. d. Phys.*, 15, 615 (1904).
[44] B. B. Boltwood, *Nature*, 76, 544 (1907).

0.71%, and 99.28%, respectively. Each emission of an alpha particle with its mass 4 and positive charge of two units thus lowers the mass and in reducing the charge by two units leaves a new residual element standing two below that of the parent in the periodic table. The emission of a beta particle with its negative charge and negligible mass is thus equivalent to adding a positive electronic charge to the nucleus. This results in a new element, standing one space higher in the periodic table. Elements of different atomic number are usually separable chemically. In this way continued investigations revealed the fact that the atom of uranium of mass 238 and atomic number 92 is the ancestor of an entire series of elements of descending atomic weights. In its continued disintegration eight alpha particles and six beta particles are emitted. The final residual atom is an isotope of lead of atomic weight 206 and atomic number 82.

Many of the intermediate products, at their discovery, were given names which though significant at that time have now become misleading and do not express the nature of the isotopes they represent. For example, uranium $X_1$ is not an isotope of uranium but rather of thorium; uranium Z and uranium $X_2$ are protactinium; and radium C and radium E are isotopes of bismuth. This genetic development from the uranium isotope of mass 238, including the half-lives of the intermediate radioactive isotopes, is shown in Figure 1.8. In addition, the neutron-induced isotope leading to the element plutonium of mass number 94 is included.

The half-life of uranium 238 is about $4.5 \times 10^9$ years, which means that the disintegration constant $\lambda$ which is $\frac{0.693}{T_{1/2}}$ has the value $4.9 \times 10^{-18}$ sec$^{-1}$. Hence a gram of pure uranium 238, which contains $2.53 \times 10^{21}$ atoms, will give rise to $2.53 \times 10^{21} \times 4.9 \times 10^{-18}$ or about 12,400 disintegrations per second. The half-life of radium, whose mass is 226 and atomic number 86, is 1590 years. Hence the disintegration constant is 1.385

$\times 10^{-11}$ sec$^{-1}$, and the $2.68 \times 10^{21}$ atoms in one gram will give rise to $37.1 \times 10^9$ disintegrations every second. This number is important in current definitions of the Curie, a unit used to express the strength of radioactive sources.

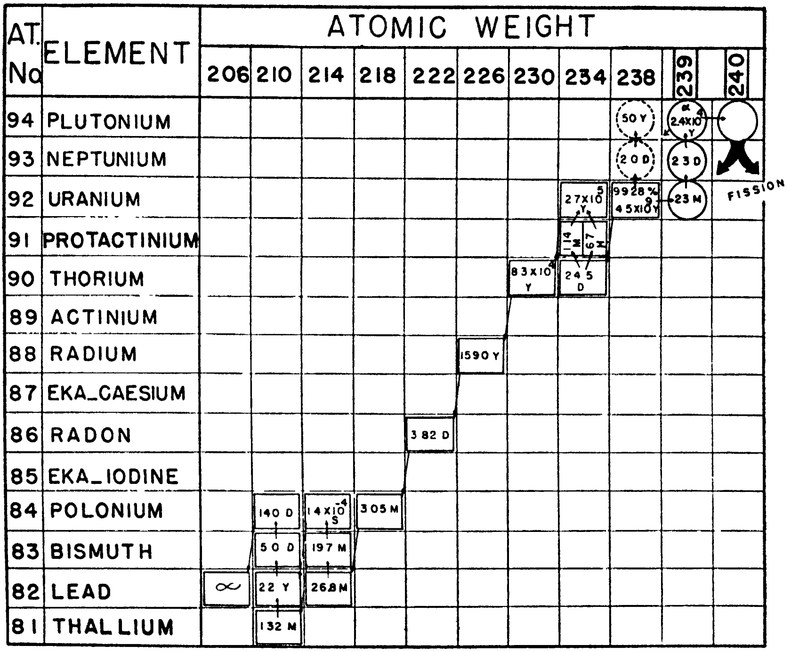

FIG. 1.8. The uranium-radium family.

**1.12. The Uranium-Actinium Family.** Another series of radioactive elements genetically related among themselves has been shown to be derived from the less abundant uranium isotope of mass 235. This parent isotope has a half-life of 7.1 $\times 10^8$ years and emits in succession seven alpha particles and four beta particles. The final residual atom is an isotope of lead of mass 207. The nature of the intermediate products is quite similar to the atoms in the parallel radium series. For example, the element of atomic number 86 is a gas called actinon, much like the corresponding element in the radium series, radon. This sequence of elements is shown schematically in Figure 1.9.

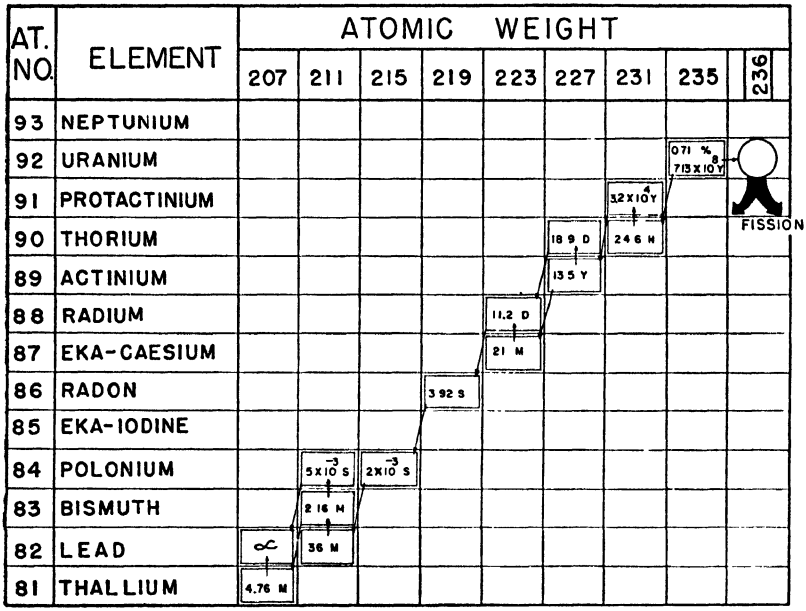

FIG. 1.9. The uranium-actinium family of radioactive atoms.

**1.13. The Thorium Family.** Another independent radioactive series has been identified, based upon the single natural isotope of thorium, whose mass is 232 and atomic number, 90. After the successive emission of six alpha particles and four beta particles the emitting atom becomes an isotope of lead, of mass 208. The element of atomic number 86 in this series is also a gas, called thoron. The thorium family, including the half-lives of the intermediate elements, is shown schematically in Figure 1.10. Thorium itself has a half-life of $1.389 \times 10^{10}$ years. Many of the intermediate products in all three families emit gamma rays in addition to the alpha or beta particles. The gamma radiation from thorium (C + C′) has been extensively used where a high energy source was desired. Its radiation is concentrated largely in a single emission energy of 2.62 Mev.

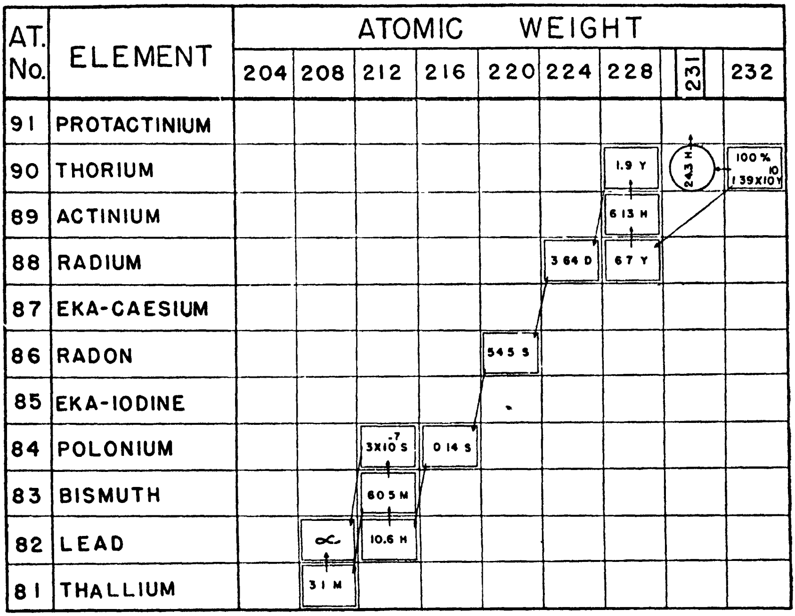

Fig. 1.10. The thorium family of radioactive elements.

**1.14. The Age of the Earth and Radioactivity.** The development of helium as a product formed in the aging of uranium, offers a method of estimating the age of the uranium. Assumptions must be made regarding the retention of the helium formed and the fact that no other source of helium is present. It is usually assumed that helium will be retained in rock when the temperature has fallen below about 1000° C. Thus, knowing the amount of helium recovered for each gram of uranium present, it is possible to compute a minimum value for the time elapsed since helium began to be formed. The decay constant for uranium 238 as now observed is $4.9 \times 10^{-18}$ $\text{sec}^{-1}$. The possibility exists that originally other isotopes of uranium with their greater disintegration constants were relatively more abundant. Assuming, however, that the isotope 238 was always preponderant, then the half-life of $4.5 \times 10^9$ years can be retained. Since each disintegrating atom yields eight alpha particles and in one half-life half of the particles disintegrate, it follows that an original gram of uranium will in one half-life produce $\frac{16}{238}$ or 0.0674 grams of helium. This quantity would represent 376 $\text{cm}^3$ under standard conditions of pressure and temperature. It is apparent that if retained in pockets in the ore to this extent it will be under high pressure and hence apt to escape, and ages computed therefrom will be minimum values. This transformation of uranium during one half-life may be represented as:

$$1 \text{ gram uranium} \rightarrow 4500 \text{ million years} \rightarrow \left\{\begin{array}{l} 0.5 \text{ gms. uranium} \\ 0.0674 \text{ gms. helium} \\ 0.4326 \text{ gms. lead } 206 \end{array}\right.$$

The first use of this method in estimating the age of rock is attributed to Strutt in 1905.[45] An extensive investigation of ores from various terrestrial sources using this method has been carried out by Paneth and his students, beginning in 1928.[46] Many subsequent investigations, particularly those by R. D. Evans and his associates,[47] have led to a fair knowledge of the age, not only of terrestrial ores but also of meteorites and hence probably of the entire solar system. These values are found to agree fairly well, indicating ages up to 2800 million years.

Other methods of comparing ages of two ores have made use of the relative abundance of different isotopes of a particular element present in the ores. Thus uranium consists of isotope 238 whose half-life is 4500 million years and isotope 235 with a half-life of only 710 million years. It might be expected that in a young ore less of the more active isotope would have disappeared so that its abundance would be greater than the

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[45] J. R. Strutt (later Lord Rayleigh), *Proc. Roy. Soc.*, **76**, 95 (1905); **82**, 168 (1909)

[46] F. A. Paneth, W. D. Urry, and W. Kolck, *Nature*, **18**, 490 (1930).

[47] C. Goodman and R. D. Evans, *Bull. Geol. Soc. Amer.*, **52**, 491 (1941).

$\frac{1}{140}$ found for terrestrial sources. No specimen of uranium has been found yielding a different ratio.[48] Similarly potassium has three isotopes whose masses are 39, 40, and 41 and whose relative abundances are 93.38%, 0.012%, and 6.61%, respectively. Isotope 40 is radioactive with a half-life variously reported as $4 \times 10^8$ years to $1.6 \times 10^9$ years. It should therefore be relatively less abundant in aged specimens of potassium. No such variations in the relative abundance of the isotopes of potassium has been observed.[49]

Since each radioactive series ends in a particular isotope of lead, then the relative abundance of the various isotopes for specimens of lead from different parts of the earth differ. By noting the excess of the isotope of mass 208 associated with the decay of thorium,[50] calculations can be made of the time required for its formation. Such computations lead to values of the age of the ores of about 2000 million years, which substantiates the results of other methods.

**1.15. The Measurement of Radioactivity.** (*a*) *The Curie.* It is apparent that with the present extensive use of radioactive materials some agreement must be made regarding the units used in measuring the activity. Radium itself is usually used as a chloride and the active content can be expressed in grams. Since a radium sample will soon generate products with which it is in equilibrium, then these separated products, although very minute in mass, will have a radioactivity comparable with that of the parent radium. Consequently a unit, now known as the "Curie," has been recognized; as originally defined it was the amount of radon in equilibrium with one gram of radium. From their comparative half-lives, namely 1590 years and 3.82 days, this amount of radon would weigh only 6.58 millionths of a gram, and under standard conditions of pressure and temperature would occupy only 0.664 $mm^3$. On pumping off this gas an additional amount will re-form according to a growth curve as shown in Figure 1.4.

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[48] A. O. Nier, *Phys. Rev.*, 55, 150 (1939).

[49] W. Schumb, R. D. Evans, and W. M. Leaders, *Jour. Amer. Chem. Soc.*, 63, 1203 (1941).

[50] P. M. Hurley and C. Goodman, *Bull. Geol. Soc. Amer.*, 52, 545 (1941).

When the radon is in equilibrium with the parent radium, each would have the same number of disintegrating atoms per second, namely, $37.1 \times 10^9$, as shown on page 25. It is now known that this number should be revised downward to perhaps $35 \times 10^9$, but because any change must be generally accepted, no attempt will be made here to introduce a revision. It has accordingly now become common practice to express the radioactivity of any specimen, regardless of the type of emission, in terms of the number of disintegrating atoms per second in the source. Thus a millicurie of radiophosphorus, which emits no gamma radiation whatever, is that quantity of radioactive material in which 37.1 million particles are disintegrating per second. Certain anomalies arise from such a definition. It often happens that a single disintegrating atom in quick succession emits more than one particle or gamma ray. Thus each atom of radio cobalt of mass 57 emits two strong gamma rays in its disintegration. Since any gamma ray usually has sufficient energy to completely traverse the detector, it is evident that the ionizing effect of a millicurie of radio cobalt would be twice as large as the ionization produced by a similar source of another isotope in which only a single gamma ray is emitted per disintegration.

It has been suggested by Condon and Curtiss[51] that a new unit be defined for expressing the strength of radioactive sources based directly upon the number of disintegrations per second. It would be reasonable to select an activity of some magnitude such as $10^6$ disintegrations per second for the unit and then express multiples and submultiples by the usual prefixes of the metric system. For this unit they propose the name "rutherford" with the abbreviation "rd."

(*b*) *The Roentgen or "r" Unit.* Gamma radiation may be detected by the same technique as that employed in measuring

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[51] E. U. Condon and L. Curtiss, *Science*, **103**, 712 (1946).

X-rays. A unit known as the "r" unit, after W. Roentgen, the discoverer of X-rays, has long been recognized in X-ray practice. This is defined as the amount of radiation that will, on passing through pure air under standard conditions, produce one electrostatic unit of ions, of one sign, per cubic centimeter. It is evident that this is no measure of the total energy of the radiation, but rather of its absorptivity. In fact, the lower the energy of the photons comprising the radiation, the greater would be the ionization per centimeter of path.

The ionization produced by a photon is accomplished by tearing away and energizing electrons, from the neutral atoms of the traversed gas. At relatively low energies this is accomplished by two processes known respectively as the photoelectric effect and the Compton effect. On the average a photon produces only about 1.5 ion-pairs per centimeter of path in normal air, compared with about 50 pairs per centimeter for beta particles and 30,000 pairs per centimeter for alpha particles. In r units, a gram of radium supplies at a distance of 1 cm an ionization equivalent to 480 r per second. The gamma radiation alone amounts to about 2.4 r per second. One of the most direct methods for measuring the ionization produced, and hence the number of r units, is to allow the radiation to pass through the gas between the oppositely charged plates of a condenser, usually cylindrical in form. The fall in potential times the electrical capacity in electrostatic units divided by the volume gives the "r" value. Easily operated and calibrated devices of this kind as usually used by roentgenologists are supplied by the Victoreen Company of Cleveland, Ohio.

In the measurement of the strength of a source of gamma rays Condon and Curtiss propose a new unit which is of such a magnitude that it will produce a radiation of one roentgen per hour at a distance of one meter. They propose for this unit the name "rhm," pronounced "rum." From the above value given for the gamma intensity from 1 gm. of radium, it follows that a gram of radium would be expressed as 0.864 rhm, or conversely one "rhm" requires 1.16 gm. of radium.

## QUESTIONS AND PROBLEMS

**1.** The atomic weight of lead as found in galena is 207.216 and from Great Bear Lake ore it has an atomic weight of 206.083. Assuming only the uranium-radium family to be responsible, what percentage of the lead is derived from uranium? If 5 gms. of lead are recovered from a certain specimen, how much helium should be in the same source? In this same specimen how many gms. of uranium would you expect if the age of the rock is $2000 \times 10^6$ years?

*Answer:* 93.5%, 4.675 gms. lead, 0.726 gm. helium, 15 gms. uranium.

**2.** A certain hospital has four grams of radium valued at $160,000. Radon is pumped off every 48 hrs. How many millicuries are obtained each time? What should be the charge for a 10 millicurie seed of radon, allowing a service charge of $2.00 per seed, a 5% interest rate, and a satisfactory depletion charge?

*Answer:* 1216 millicuries, $2.365.

**3.** How many beta particles are emitted per second by the above-mentioned radium in equilibrium with its daughter products?

*Answer:* $59.36 \times 10^{10}$ beta particles per second.

**4.** How many neutrinos will pass in one second through the body of a man which presents a normal area of 6 sq. ft., at a distance of 1000 miles from the above radium?

*Answer:* 0.01017 per second.

**5.** Compare the atomic weights of deuterium on the "physical" and on the "chemical" scales. Compute the atomic weight of hydrogen from the mass-spectographic data on its isotopes.

*Answer:* 2.014722 (phys.), 2.01418 (chem.); 1.00834 ($H$).

**6.** The packing fraction for plutonium 239 is $+4.0$, and for barium 139 and strontium 89 the values are $-6.1$ and $-8.1$ all in $10^{-4}$. If a plutonium atom undergoes fission, producing the above two atoms, how many neutrons are set free and how much mass disappears? What is the total release of energy in electron-volts and in ergs per atom of plutonium?

*Answer:* 11 neutrons plus original, 0.15425 mass units, 144 Mev, $2.304 \times 10^{-4}$ ergs.

## CHAPTER 2

# THE DETECTION OF RADIATION

**2.1. The Fluorescent Method.** Many substances when exposed even to invisible radiation like ultraviolet or X-rays become copious emitters of visible light. In some of these substances the emission of light persists long after the exposure to radiation. In many other substances the glowing lasts only a fraction of a second after the excitation has vanished. The former phenomenon is called phosphorescence and the latter is termed fluorescence. This, then, allows the detection of radiation by noting the luminosity of a prepared screen, exposed to the radiation. Such materials now commonly used are platinobarium cyanide, calcium tungstate, or zinc sulphide.

It was the fluorescing of the glass walls of an X-ray tube that led Becquerel to look for what he regarded as invisible fluorescence. That is, a photographic plate was protected from various fluorescing substances by black paper. On using the double sulphate of uranium and potassium, he found that the wrapped photographic plate became activated whether the salt was illuminated or not.

A device known as the spinthariscope, attributed to Sir William Crookes[1] in 1903, was used in early studies of alpha radiation. Figure 3.1 shows a form of the apparatus as used later by Rutherford in studying the first induced nuclear disintegrations. The individual alpha particles from the source *S*, or the recoil protons from the gas, will on striking the screen appear as momentarily illuminated spots when viewed through the microscope, so that if not too numerous they can be counted.

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[1] W. Crookes, *Proc. Roy. Soc.*, **71**, 405 (1903).

By knowing the solid angle subtended at the source the total emission can be found.

The device was used for beta radiation by Regener.[2] In this case each scintillation is probably due to the simultaneous impact of several beta particles, as it is doubtful if a single electron could produce an observable effect.

**2.2. The Photographic Method.** It has been shown that any ionizing radiation or particle will, on absorption in the emulsion of a photographic plate, produce activation. In the case of gamma radiation the action on the silver bromide crystals is undoubtedly cumulative. Heavily ionizing particles like alpha particles, protons, or deuterons are sufficiently energetic to activate some individual crystal grains through which they pass, although not necessarily all. As a consequence, on development, the actual track of the particle is revealed.

A technique making use of such emulsion tracks to measure the energy of the incident particles has been developed by Wilkins.[3] The average number of electron volts per grain may be determined and then it is necessary only to count the number of activated grains. The method is tedious, and is most successful when used under dark-field illumination. In studying induced disintegration the emulsion may be impregnated with the material to be bombarded. The recoiling particles are thus observed in the developed layer. Figure 4.2*C* shows one of these tracks with a magnification of 900. This track represents the two oppositely directed alpha particles arising from a lithium 7 nucleus, struck by a neutron.

A photographic technique particularly applicable to studies involving radioactive materials as tracers in biological work, was reported by Lacassagne and Lattés in 1924.[4] A section of the tissue with the absorbed radioactive material is placed in close contact with the photographic plate for a suitable time.

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[2] W. Regener, *Verh. Deut. Phys. Ges.*, **19**, 78 (1908).

[3] T. R. Wilkins and H. St. Helens, *Phys. Rev.*, **54**, 783 (1938); L. C. Martin and T. R. Wilkins, *Jour. Opt. Soc. Amer.*, **27**, 340 (1337).

[4] Mme. J. Lattés and A. Lacassagne, *Comptes Rendus*, **178**, 630 (1924).

The plate will be activated in areas contiguous to the radioactivity but not in those areas close to tissue carrying no radioactive material. Such photographs are termed "autoradiograms" and show directly the distribution of the tracer element. Examples of this technique are shown in Figure 11.1 and Figure 11.3*B*.

**2.3. Ionization Chambers.** Becquerel observed that a charged electroscope would be discharged if uranium was brought near its terminal. Such a device as shown in Figure 2.1*A* was one of the first simple instruments used to compare radioactivities. By placing the specimens in order on the terminal plate, their activities are inversely proportional to the times required for the leaves of the electroscope to collapse over a certain definite portion of the angular scale.

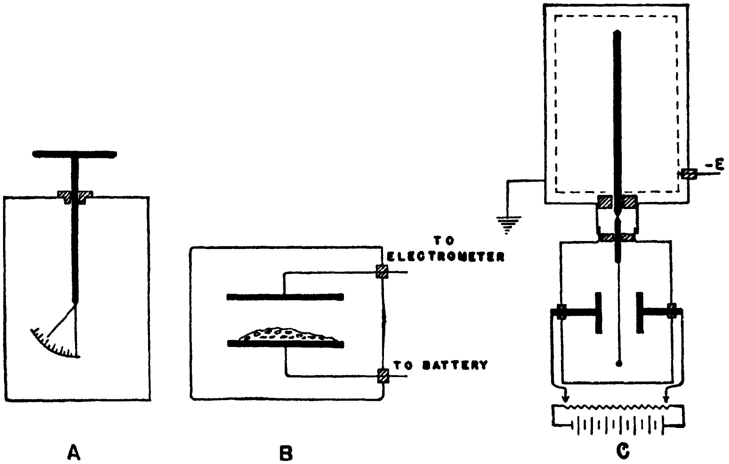

FIG. 2.1. (*A*) Electroscope; (*B*) ionization electrometer; (*C*) ionization chamber with string electrometer.

Another arrangement, shown in Figure 2.1*B*, was used by Madame Curie in a general investigation of the radioactivity of a wide variety of substances. The specimen is placed on the bottom plate and any ionization produced, results in an ionization current which is measured by a sensitive electrometer. As the conductance between the plates may be affected by other factors such as temperature and humidity, sometimes false conclusions can be formed.

An ionization chamber connected to a string electrometer is shown in Figure 2.1*C*. This is a very satisfactory arrangement for detecting and measuring the activity. The outer case of the chamber is capable of holding gases at pressures up to several atmospheres and is electrically grounded. Inside, and insulated from the outer case, is a cylinder of screen wire maintained at a high electric potential. A central insulated rod is connected through a sulphur bushing to a very fine wire, or quartz fiber which has been made electrically conducting by a thin sputtered metallic coating. The fiber is held under a slight tension between two oppositely charged plates and is viewed through a microscope provided with an etched scale in its eyepiece. The charging of the fiber causes it to drift toward the plate of opposite sign. To restore the fiber to its initial position it is momentarily grounded. The sensitivity of the instrument can be varied at will, by changing the potential difference between the plates. The over-all sensitivity can be increased by using in the chamber a heavy gas, such as freon ($CCl_2F_2$), whose molecular weight is about 129.

**2.4. The Vacuum-Tube Electrometer.** The ions produced in the ionization chamber by the incident radiation give rise to an ionization current. The charge associated with the 100,000 ion-pairs which would be produced by a single alpha particle traveling approximately a centimeter in normal air would amount to about $3 \times 10^{-14}$ coulombs. If this average charge should pass through a high resistance of, say, $3 \times 10^{10}$ ohms in one second, then a difference of potential of approximately one millivolt would exist across the high resistance.

Any change in the rate of ionization in the chamber would result in a corresponding change in this voltage. By allowing this small voltage change to swing the grid potential of a special

FP54 three-electrode vacuum tube, correspondingly large variations would occur in the plate circuit of the vacuum tube.[5] These changes in plate current can be indicated by a direct-reading galvanometer. An arrangement of this type is shown in Figure 2.2. Since the plate current, even with no ionization, may be appreciable, it is desirable to use a potentiometer circuit to offset the steady initial current through the galvanometer.

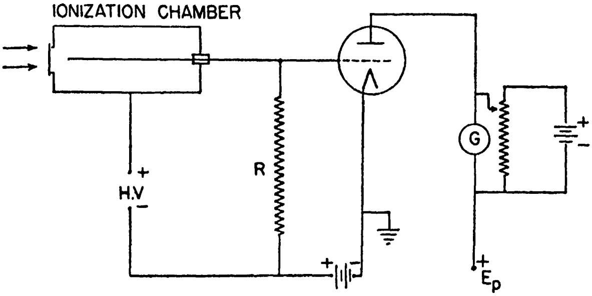

Fig. 2.2. A vacuum tube electrometer.

Since it is desired that the circuit be stable in order to make reliable quantitative measurements, and since the amplification of the vacuum tube is being pushed to the limit, great care must be taken to guard against such disturbing factors as temperature changes, humidity changes, and fluctuations in supply voltages. It is usually found desirable to enclose the entire system in an electrically shielded chamber and the vacuum tube and associated high resistors in an evacuated volume. With this care, the device is an accurate, quick-acting detector for even very weak radiation.

**2.5. Point Counters.** Many other electrical systems have been devised to study the radiation from radioactive bodies. Some of the devices will indicate and record the transit of a single particle. Most of these developments have been based upon the pioneer work of Gorton in 1905.[6] He observed that the applied voltage necessary to produce a breakdown discharge from a charged conducting point could be greatly varied by irradiating the gas in the neighborhood of the point. On using the light from an arc, X-rays, or radioactivity, breakdown was found to occur at 1000 or more volts less than when no radiation was present. A chamber of this sort is shown in Figure 2.3*A*.

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[5] L. A. DuBridge and H. Brown, *Rev. Sci. Inst.*, 4, 532 (1933); D. Penick, *Rev. Sci Inst.*, 6, 115 (1935).

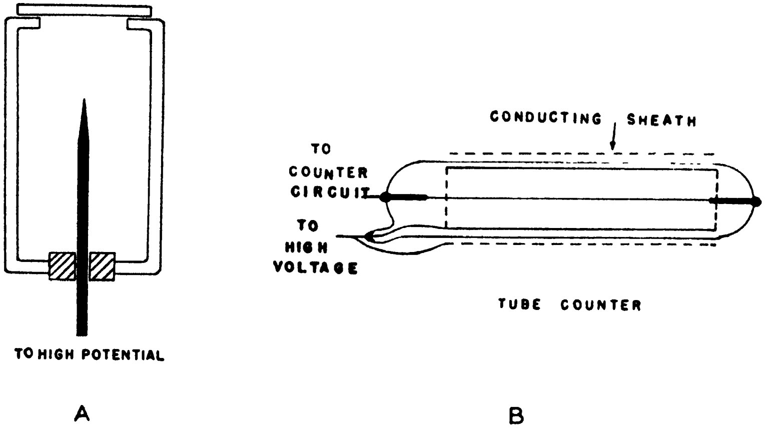

FIG. 2.3. (*A*) Charged point detector; (*B*) Geiger tube.

A single 7 Mev alpha ray will produce about 200,000 pairs of ions in its traversal of the gas of an ionization cell. This would amount to one ten-thousandth electrostatic unit each of positive and of negative electricity. This quantity might be further increased by secondary ionization in the strong electric field so as to give an indication of the single alpha particle. In 1908, Rutherford and Geiger[7] described a system in which a high voltage was applied to a point-shaped conductor so as to bring it to a potential just less than breakdown. In this strong electric field any ions formed will be accelerated and in turn they will produce new ions by collision with neutral molecules.

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[6] F. R. Gorton, *Verh. Deut. Phys. Ges.*, 7.2, 42 (1905).

[7] E. Rutherford and W. Geiger, *Proc. Roy. Soc. A*, 81, 141 (1908).

As a result a single ionizing particle may, by multiple ionization, be sufficient to cause a discharge. If a condenser is across the gap, with a high resistance in series with the source of potential, then the discharge results in a lowering of the voltage so that the current ceases or is "quenched." Without any further ionization, the high potential is again established and ready for the next firing. Such a circuit is rather slow.

By reducing the pressure in the chamber and using a fine wire at the axis of a cylinder instead of a point, and noting the discharge on a string electrometer as in Figure 2.1*C*, it became possible to count individual pulses occurring at a rate up to five per minute. Improvements in the string electrometer were made and a photographic arrangement was added so that the continuous motion of the string could be recorded on a moving film. With this apparatus counts were recorded up to 1000 per minute.

**2.6. Tube Counters.** Numerous papers have appeared dealing with the tube originally introduced by Rutherford and Geiger and now usually called a "Geiger" tube. Many of these deal with improvements in its accompanying recording circuit. The most commonly used tube takes the form shown in Figure 2.3*B*, although they may be made in many other shapes for special applications. A fine wire, usually tungsten, lies at the axis of a metal cylinder, enclosed in a concentric cylindrical sheath of glass. The tube performance is usually improved by having another conducting cylindrical sheath outside the glass and connected to the inner cylinder, so that the glass walls are free from an electric field. The glass sheath may be provided with a very thin window so that easily absorbed radiations may be studied. This can be accomplished by blowing a bubble at one end of the glass so that its thickness is reduced to the order of only a few microns.

The tube is first evacuated and the surfaces cleaned by sputtering at a high potential. Hydrogen gas is then added at a pressure up to about 10 cm of mercury. A slight amount of other gases such as argon, oxygen, or organic vapors up to about 10% is sometimes added. These vapors have been found to aid in quenching the discharge. The output of the tube is passed on to a counting circuit. No unanimity of opinion exists in explaining the action within the counter tube as the discharge is initiated and quenched. Emeléus [8] concluded that the secondary ionization within the tube is done completely by the positive ions formed. The opposite view has been presented in a more recent paper of Montgomery and Montgomery [9] which very well summarizes the progress on the development of the Geiger tube.

The action within a counter tube whose central wire is at a high positive potential may be somewhat as follows. A single ion-pair formed between the electrodes will be followed by a drift of each ion, the electron toward the positive central wire and the heavy positive ion toward the cylindrical cathode. The mobility of the electron may be one thousand times that of the positive ion so that it soon acquires sufficient velocity to produce a new pair of ions on collision. This new electron will travel along toward the anode and may in turn produce another pair of ions. This cumulating drift of electrons may be termed an "electron avalanche." Some electrons will recombine with positive ions, a process which may be accompanied by the emission of photons. In turn, if sufficiently energetic, the photons may eject photoelectrons from atoms in other remote regions of the tube, thus aiding in the avalanche.

The positive ions left behind by the fast-moving electrons appear as a positive space charge around the positive wire, which in turn reduces the electric field. This whole process may take place in one-millionth of a second and a billion electrons may have reached the wire. The current established must be quickly quenched, either by the vapor in the tube or by the accompanying circuit. Other factors to be considered in the operation of the tube are: the loss of ions by recombination, the ability of the heavy positive ion to attract negative ions from a surface of metal which it approaches, and the frequent production of several negative ions by the impact of a single electron.

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[8] K. Emeléus, *Proc. Comb. Phil. Soc.*, 22, 676 (1925).

[9] C. G. Montgomery and D. D. Montgomery, *Jour. Fran. Inst.*, 231, 447, 509 (1941).

Various arrangements may be employed in applying the high voltage to the Geiger tube—that is, instead of applying the high voltage to the wire, it may be applied to the cylinder. The performance of the tube can be found by using some standard source and noting the number of output counts per second as the applied voltage is increased. A typical performance curve for a hydrogen-filled tube is shown in Figure 2.4. No counts will occur until a certain minimum voltage, $V_1$, is applied. The number of counts per second increases as the voltage is stepped up until some value, $V_s$, not sharply defined, is attained, beyond which little or no increase in the counting rate occurs. Finally, at voltages greater than $V_M$ the counting rate again increases. It is essential that the plateau $V_s$ to $V_M$ exist if accurate quantitative results are desired. Without such a plateau any observed change in the number of

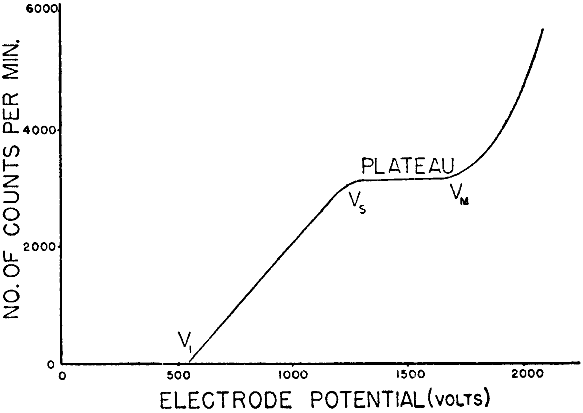

Fig. 2.4. Variation of counting rate with increasing voltage.

pulses per second might be due to a change in voltage and not to a change in the intensity of the source.

**2.7. Counter Circuits.** The development of the multielectrode vacuum tube has made possible electrical circuits which, when used with the Geiger tube, can resolve and count the individual pulses even though they occur in extremely rapid succession. The elementary use of the vacuum tube in this connection is simply illustrated by Figure 2.5. The plate current in the vacuum tube depends upon the potential of the control grid, represented by point *n*. With no ionization in the Geiger tube, no current flows through the high resistance and *s* and *m* are at the same positive potential which is communicated through the coupling condenser *C* to the grid, so that the plate current is sufficiently large to energize the relay. An incident particle produces ionization in the Geiger tube which is accompanied by a current through the high resistance and hence a lowering of the potential of point *m* and also of the control grid. This results in a decrease in the plate current sufficient to cause the relay contact to be released, and operate any indicating or registering device. At the same time, the decrease in the plate current results in an increase in the voltage across the neon glow tube, causing it to flash momentarily.

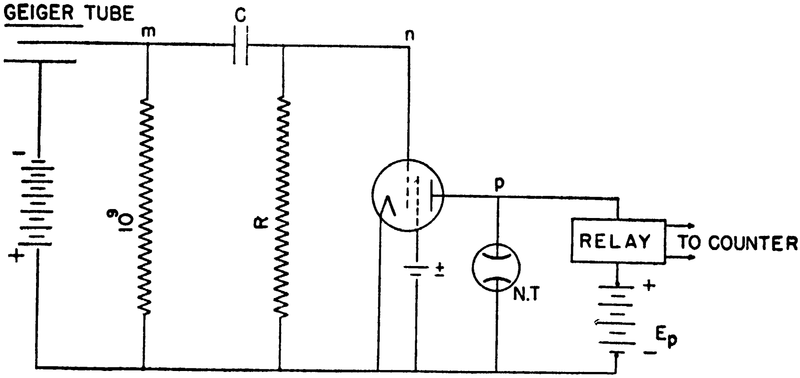

Fig. 2.5. Vacuum tube circuit for recording pulses in Geiger tube.

The combination of decreased voltage across the Geiger tube and the nature of the discharge, act to quench the current and establish the original conditions. The maximum number of counts per minute that can be recorded by this circuit without loss is not great.

*a. The Neher-Harper Circuit.* A modification of the circuit capable of responding to an input frequency up to 200,000 particles per minute without serious loss, is shown [10] in Figure 2.6.

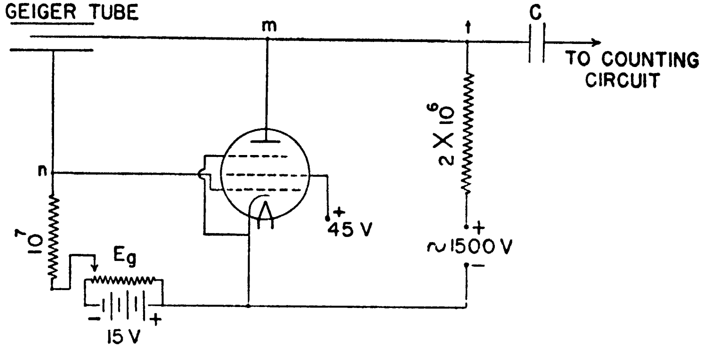

FIG. 2.6. Neher-Harper circuit for Geiger tube.

The potential of point *n*, which is that of the control grid, is adjusted to a slightly negative value, so that the plate current assumes a small normal value. Any ionization due to an incident particle in the Geiger tube leads to an increase in the positive potential of *n*. This increase of potential in the control grid in turn allows an increase in the plate current and hence a decrease in the potential of point *m*. This decreased voltage at the Geiger tube quenches the current and re-establishes the original conditions. The momentary decrease in potential at *t* is communicated through the coupling condenser *C* to any auxiliary counting circuit.

*b. Coincidence Circuit.* Frequently it is desired to record only those events which occur simultaneously in two Geiger tubes. A circuit capable of serving in this manner as first used by Rossi[11] is shown in Figure 2.7. The potentials of the grids of both tubes are adjusted to values sufficiently positive to establish the plate currents through both tubes *A* and *B* to a certain normal value. At the same time the grid potential of tube *D*, which may be a gas-filled triode, is made sufficiently negative to reduce its plate current to zero. Any ionizing particle entering the upper Geiger tube results in the potential of point *m* and hence that of the control grid of tube *A* becoming less positive, so that its plate current is reduced to zero. This raises the potential of point *t* and hence of the control grid of tube *D*, but not enough to cause it to fire. If, however, particles enter both Geiger tubes simultaneously, then the potential of *t* increases sufficiently to fire the triode *D*, and give a simple impulse to the counter. In cosmic-ray studies these coincidence circuits have played an important role. In a recent investigation[12] on the production of mesons at high altitudes, 46 Geiger tubes were employed in a single circuit so that they could be arranged in 10 different 3-, 4-, and 5-fold coincidence sets.

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[10] H. V. Neher and W. Harper, *Phys. Rev.*, **49**, 940 (1936); see also T. Johnson and J. Street, *Jour. Fran. Inst.*, **215**, 239 (1933).

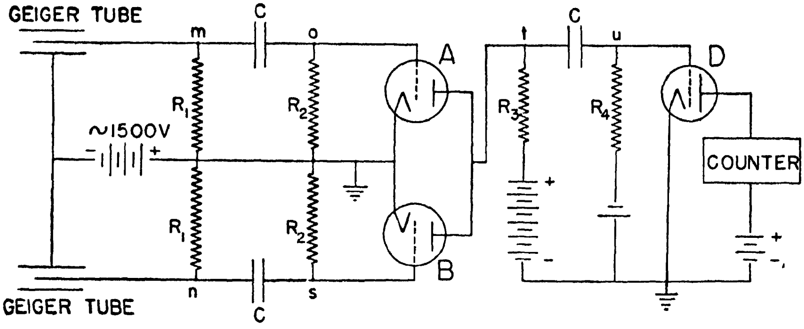

FIG. 2.7. Coincidence circuit for Geiger tubes.

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[11] B. Rossi, *Nature*, **125**, 636 (1930).

[12] J. Tabin, *Phys. Rev.*, **65**, 86 (1944); see also M. Schein, W. Jesse, and E. Wollan, *Phys. Rev.*, **56**. 613 (1939).

*c. Scaling Circuits.* Mechanical registering devices can usually not operate at a frequency greater than three or four thousand per minute. For a speed of this order or greater it is common practice to arrange[13] a circuit of vacuum tubes so that the mechanical register records a single count for each 2, 4, 8, or 16 incident particles, yet by a system of glow lamps or a direct-reading meter the additional single particles can be numbered. These circuits are made up of a succession of "scale of two" counters so that the over-all scaling factor is $2^n$, where $n$ is the number of times the simple unit of two is repeated. Various types of tubes and arrangements of components in the circuit have been used. A simple two-tube unit using thyratrons is shown in Figure 2.8. Successive incoming pulses fire the two tubes *A* and *B* alternately, but only the firing of *B* passes the impulse on to the next set of thyratrons. A glow lamp in the circuit of *A* tells when it has fired. The mechanical counter is connected in the output circuit of the last tube. For exceedingly high rates of counting scaling circuits may be connected together thus two scale-of-sixteen counters in series can be used to give a scaling factor of 256.

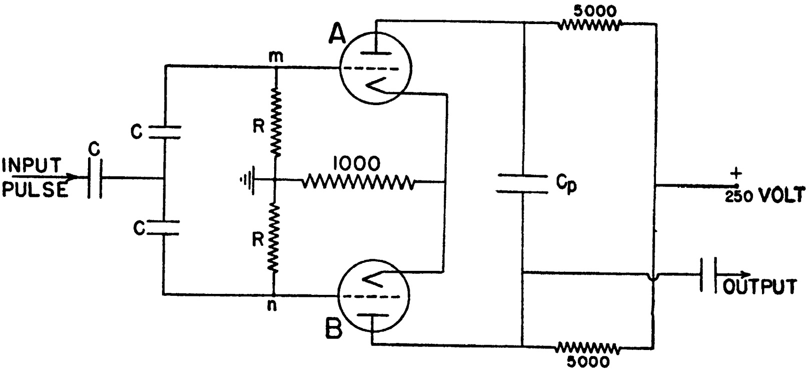

FIG. 2.8. "Scale of two" circuit for recording pulses.

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[13] See, for example: W. G. Shepherd and R. O. Haxby, *Rev. Sci. Inst.*, 7, 425 (1936): E. C. Stevenson and I. Getting, *Rev. Sci. Inst.*, 8, 414 (1937); and J. Lawson and H. Lifshutz, *Rev. Sci. Inst.*, 9, 83 (1938).

**2.8. The Electron Multiplier.** On bombarding certain surfaces by electrons it may happen that each impinging electron expels several electrons from the struck surface. If these electrons are caught in an electric field and driven against another similar surface, each of them may again give rise to several electrons. This process may be repeated several times so that the original electron finally is represented by $a^n$ electrons, where $a$ is the multiplying factor at each surface which may be as much as 8, and $n$ is the number of stages. Such an arrangement as currently used by the Western Electric Company

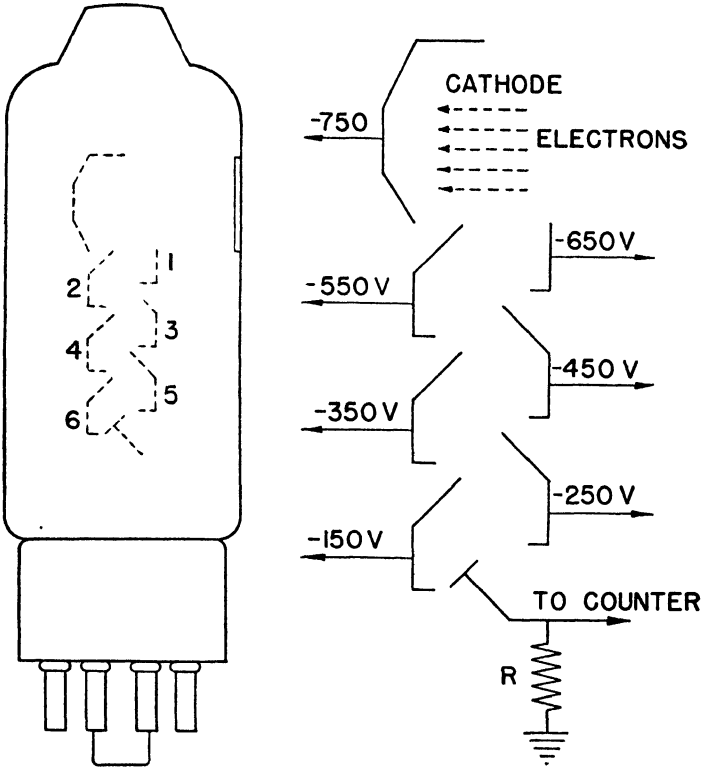

Fig. 2.9. Electron multiplier, assembly and electrode arrangement.

is shown in Figure 2.9. Care must be taken in arranging successive surfaces[14] both as to shape and placement so that each surface is effective in contributing to the electron multiplication. The initial impulse may be from electrons as beta radiation or it may be instigated by photons which photoelectrically eject electrons from the first surface. These initial electrons are accelerated here in seven steps, each potential fall being about 100 volts. The secondary emission of each surface is found to be a maximum for a potential of about 400 volts, but this is not attained in practice. Surfaces of pure beryllium have been successfully used, but the most commonly employed coating consists of caesium oxide or some similar material.

**2.9. Wilson Cloud Chambers.** In 1911, a device was demonstrated by C. T. R. Wilson[15] which made it possible for the first time to see and photograph the "track" of an individual particle. This apparatus functions because of the fact that in a supersaturated vapor, condensing droplets will form, if possible, on any electrically charged particles that are present. For vapors that have a negative specific heat under the condition of saturation, a supersaturated condition can be attained by producing a sudden increase in the volume containing the saturated vapor. For saturated vapors with a positive specific heat, supersaturation can be produced by suddenly reducing the volume. Water vapor and many of the alcohols have negative specific heats and serve well in chambers of the first kind.

Wilson decided that as supersaturation increases, the negative ions first serve as centers of condensation. This will occur when the volume occupied by the saturated vapor is increased about 25%. For an increase in volume of 31% both negative and positive ions serve as nuclei of droplets. For expansions greater than 38% a dense cloud will form even without the presence of ions. An alpha particle traversing the gas of the chamber may produce on the average 100,000 ions per cm of path whereas an electron or beta particle will produce only about one one-hundredth as many. Consequently it is relatively easy to observe the tracks of alpha particles.

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[14] See V. K. Zworkian and J. A. Rajchman, *Proc. I.R.E.*, **27**, 558 (1939); J. R. Pierce, *Bell Lab. Record,* **16**, 305 (1938); J. R. Pierce and R. Winans, *Rev. Sci. Inst.*, **12**, 269 (1941), and J. S. Allen, *Phys. Rev.*, **55**, 966 (1939).

[15] C. T. R. Wilson, *Proc. Roy. Soc. A*, **85**, 285 (1911).

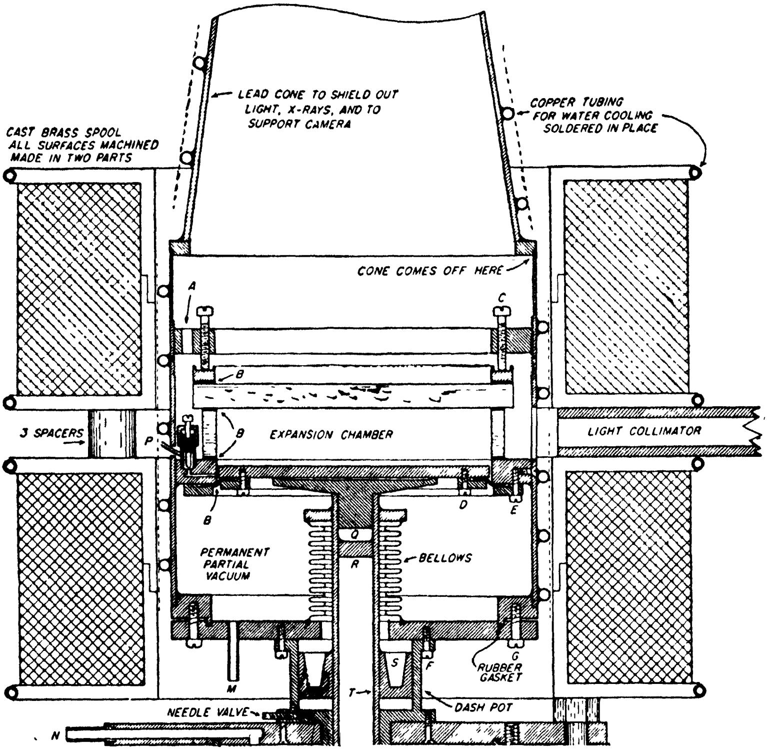
LEAD CONE TO SHIELD OUT LIGHT, X-RAYS, AND TO SUPPORT CAMERA
COPPER TUBING FOR WATER COOLING SOLDERED IN PLACE
CAST BRASS SPOOL ALL SURFACES MACHINED MADE IN TWO PARTS
CONE COMES OFF HERE
A
C
B
3 SPACERS
P
B
EXPANSION CHAMBER
LIGHT COLLIMATOR
B
D
E
Q
PERMANENT PARTIAL VACUUM
R
BELLOWS
M
S
F
G
RUBBER GASKET
T
NEEDLE VALVE
DASH POT
N

Fig. 2.10. Detail of a Wilson cloud chamber (Crane).

Figure 2.10 shows schematically the arrangement of the working parts in a currently used cloud chamber.[16] This device is capable of recording satisfactorily the tracks obtained with expansions occurring at the rate of 120 per hour. An electric

[16] H. R. Crane, *Rev. Sci. Inst.*, **8**, 440 (1937); see also O. Dahl, L. Hafstad, and M. A. Tuve, *Phys. Rev.*, **4**, 373 (1933); J. R. Richardson, *Phys. Rev.*, **50**, 999 (1936); F. N. D. Kurie, *Phys. Rev.*, **47**, 97 (1935).

field of several volts per cm is applied to the chamber up until about one-fortieth of a second before the track is to be observed. This sweeping field effectively removes the ions that would have diffused throughout the chamber. At the right moment after the expansion is completed the chamber is momentarily illuminated. The original light source used by Wilson was a mercury-vapor lamp excited by the sudden momentary discharge of a condenser. This same type of illumination can still be effectively used with improved lamps that give an intensity many-fold that of the earlier design.

A measurable magnetic field is applied perpendicular to the floor of the chamber and hence perpendicular to the velocity of the particles to be photographed, so that their paths are circular. By noting the radii of curvature of the tracks their momenta and hence their energies can be determined. For best results it is important that the particle undergo no scattering collision during its path, for in that event its radius of curvature cannot be accurately determined. To reduce this scattering, hydrogen is used instead of air in the chamber along with the saturated water or alcohol vapor.

For alpha particles the source is usually placed directly in the chamber. Beta rays may be sent into the chamber through a thin window with little loss in energy. Gamma rays are studied by observing the electrons originating in the chamber because of the Compton effect, the photoelectric effect, or by electron pair formation. For the Compton effect, a thin sheet of light material such as carbon is placed within the chamber and irradiated with the gamma radiation. For the latter two effects a thin layer of lead is put in the chamber in a similar manner. Neutrons are studied by observing the recoil protons arising because of the impact of the neutrons on any hydrogenous material within the chamber. The hydrogen gas and water vapor serve very satisfactorily in that capacity.

Photographs may be taken with either a single camera or better with a stereoscopic camera. By re-projection on a screen, the image can be observed and studied. The types of photographs obtained for the various particles are shown in later figures. Alpha particles are presented in Figure 4.2*A* and *B*, beta particles in Figure 5.4*A*, an electron pair due to a gamma ray in Figure 5.4*B*, and recoil protons due to neutrons in Figure 7.1. The discrete energy of the alpha particles is revealed by the equal length of the tracks. The wide spread in the radii of the paths of the beta particles reveals the continuous distribution of the beta spectrum. The recoil protons due to the neutrons are short in range due to the high gas pressure in the chamber. Since the energy of a photon is discrete, the precise measurement of a single electron pair should correctly evaluate that gamma ray energy.

Qualitatively, the value of cloud-chamber observations cannot be challenged. In many instances, however, because of the failure to observe proper criteria in the selection of tracks for measurement and the failure to recognize the effects due to scattering and convection, the quantitative results have been lacking in exactness, and misleading in their interpretation.

**2.10. The Beta Ray Spectrometer.** The beta rays from excited nuclei consist of electrons varying in energy from a certain maximum value down to zero. The distribution of the number of particles in each energy group seems to follow a certain natural law of probability. To observe this distribution beta spectrometers of various designs have been developed.

*a. Magnetic Semicircular Focusing Spectrometer.* Figure 2.11 represents a very useful and practical form of spectrometer as devised by Danysz [17] in 1912. It was later improved by Robinson and Rutherford [18] and has been subsequently used in many investigations.

The source of radiation is placed at *S* and a photographic plate is situated as shown perpendicular to the plane of the figure. The source at *S* sends out a bundle of particles through the aperture *AB*. A uniform magnetic field is directed perpendicularly into the figure. Those particles having the same velocity will describe circles of the same diameter. If *AB* is located in the plane of the photographic plate and is not too wide, then all electrons of the same energy will converge almost at the same point *P* on the photographic plate. Actually the greatest range is attained by the particles through a point *C* at the center of the slit, situated on a perpendicular from *S*. Those rays on either side of *C* strike the plate at a point slightly less distant from the slit than *P*, thus giving a diffuse image with a sharp outside edge.

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[17] J. Danysz, *Le Radium*, 9, 1 (1912); 10, 4 (1913).

[18] H. Robinson and E. Rutherford, *Phil. Mag.*, 26, 717 (1913).

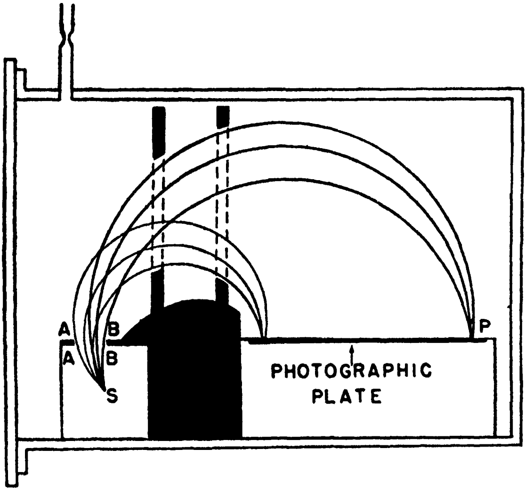

Fig. 2.11. Magnetic semicircular focusing beta ray spectrometer.

Beta rays of different energies would result in images *P* at different distances from the slit. Instead of the photographic plate it is now more common to place a slit at *P* through which the electrons pass into a Geiger tube, connected to a counting circuit. In this case the particles received travel on circles of the same diameter and different energies are brought to the Geiger tube by varying the deflecting magnetic field.

When natural radioactive substances were first examined in this device it was found that they exhibited certain "lines" representing definite energy groups superimposed on a continuous background. These lines of discrete energies are not true beta rays but are really due to gamma rays that have been internally converted. In this process the gamma ray, in getting out of its parent atom, gives up its complete energy to an orbital electron of the same atom, such as a K, L, or M electron. Monoenergetic gamma rays from an assembly of such atoms will thus be represented by a few groups of electrons each differing from the discrete gamma energy by the binding energy characteristic of the K, L, M, etc., levels.

The relationship between the energy of a beta particle and the radius of its path may be computed. For the circular motion of the electron $e$, the force toward the center due to a magnetic induction $B$ and velocity $v$ is

$$Bev = \frac{mv^2}{\rho} \tag{2.1}$$

in which $\rho$ is the radius of the path. The mass $m$ is the relativity mass, equal to $m_o(1 - \beta^2)^{-1/2}$ where $m_o$ is the rest mass and $\beta$ is the ratio of the velocity of the electron $v$ to the velocity of light $c$. The momentum $P$ of the particle is then

$$P = mv = \frac{m_o v}{\sqrt{1 - \beta^2}} = Be\rho \tag{2.2}$$

The energy $W$ of the particle in relativity theory is

$$W = mc^2 - m_oc^2 = \frac{m_oc^2}{\sqrt{1 - \beta^2}} - m_oc^2 \tag{2.3}$$

On expansion this becomes

$$W = \frac{1}{2} m_ov^2 \left[ 1 + \frac{3}{4}\frac{v^2}{c^2} + \frac{15}{24}\frac{v^4}{c^4} + \cdots \right] \tag{2.4}$$

which shows how the classical value for the kinetic energy of high-speed beta particles must be corrected, as $\beta$ increases in value toward unity. An explicit solution combining equations 2.2 and 2.3 gives

$$P = \frac{1}{c}[W^2 + 2m_0c^2W]^{1/2} \tag{2.5}$$

and the observed product $B\rho$ is approximately

$$B\rho = \frac{1}{ce}[W^2 + 2m_0c^2W]^{1/2} \tag{2.6}$$

This relationship is shown graphically in Figure 2.12, so that in practice the observed $B\rho$ can be fitted to the curve and the value of $W$ in Kev read off directly. It is apparent that at high energies the value of $B\rho$ increases linearly with energy $W$. In the Appendix, Table A III, data are given for electron energies up to 15 or more Mev.

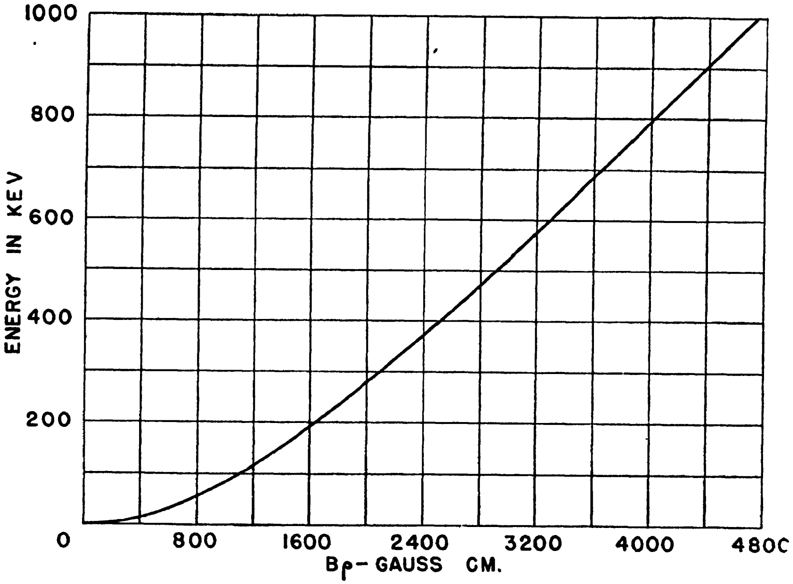

FIG. 2.12. Energy-momentum relationship for beta particles.

*b. The Electron Lens.* A type of beta spectrometer known as the electron lens is shown in Figure 2.13. A radioactive source

*S* is placed on the axis at one end of an evacuated cylinder. The cylinder is surrounded by a solenoidal wound conductor. At the other end of the cylinder is placed a detecting tube. Between the detecting tube and the source is a heavy absorber of lead, as shown, so that no radiation can be received directly. An arrangement of this sort was first suggested by Kapitza and was constructed and used by Tricker in 1924.[19] For any current through the solenoidal winding an almost uniform magnetic field will be set up through the coil parallel to its axis, whose value is given by the expression $0.4\pi nI$, where $n$ is the number of turns per cm and $I$ is the electric current in amperes.

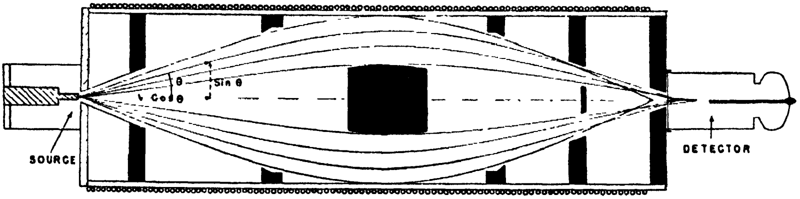

FIG. 2.13. Solenoidal wound electron lens spectrometer.

Any electron $e$ starting out from the source $s$, with a velocity $v$, making an angle $\theta$ with the axis, will experience a force causing it to execute a helical path. The component of the velocity $v$ along the axis is $v \cos \theta$ and this component carries the electron from left to right with a uniform speed. The radial component of velocity $v \sin \theta$ is at right angles to the magnetic induction $B$ and hence the electron experiences a force $Bev \sin \theta$. As a result of this force the electron will trace out a circular path as viewed along the axis, at the same time that it is being transported. Some electrons will have precisely the right velocity for a particular magnetic field so that they just traverse a complete circle of radius $R$, as shown in Figure 2.14, while they are carried along the tube from the source to the detector a distance $L$. At the midpoint they are at their maximum displacement $2R$ from the axis. They then arrive back again at the axis tangentially just at the detector. In order that this will happen, the time of transit in the circle, traversing the distance $2\pi R$ at the speed $v \sin \theta$, must just equal the time of transport through the distance $L$ by the speed $v \cos \theta$. This can be expressed as

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[19] R. A. Tricker, *Proc. Camb. Phil. Soc.*, 22, 454 (1924); see also C. M. Witcher, *Phys. Rev.*, 60, 32 (1941).

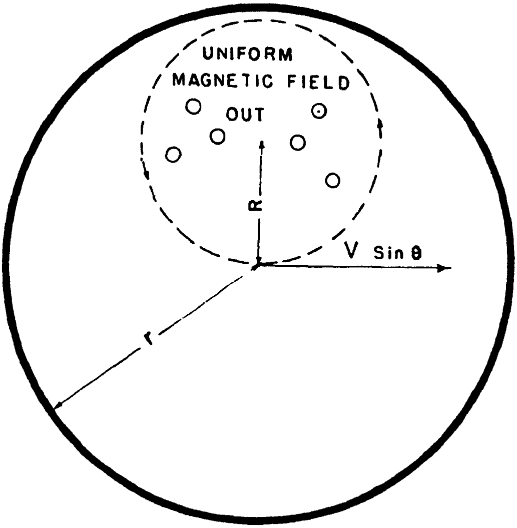

FIG. 2.14. End view of electron lens spectrometer showing projected motion of electron.

$$\frac{2\pi R}{v \sin \theta} = \frac{L}{v \cos \theta}, \quad \text{or} \quad \cot \theta = \frac{L}{2\pi R} \tag{2.7}$$

Only those particles starting at this angle $\theta$ can be successfully received.

From equation 2.1 it follows that

$$\rho = R = \frac{mv \sin \theta}{Be} = \frac{L \tan \theta}{2\pi} \tag{2.8}$$

Hence the momentum of the collected particles $mv$, which started out from the source $S$ along the surface of a cone through the system of baffles, is

$$mv = \frac{BeL}{2\pi \cos \theta} = CB = kI \tag{2.9}$$

where $C$ and $k$ are constants. That is, the momentum of the collected particles varies linearly with the electric current in the solenoid. It is evident that the instrument can be calibrated for all energies by observing the electric current required for the transmission of electrons of any single known energy. An additional advantage of this type of spectrometer is that fairly weak radioactive sources can be studied since, in effect, the detector subtends a large solid angle at the source.

This same principle, except that the electrical conductors are bunched in a short coil, is used in focusing the beam in electron microscopes. Spectrometers for beta rays have been similarly constructed.[20] By changing the current through the winding the magnetic induction $B$ is changed and a different energy group of electrons will negotiate the baffle system and arrive at the detector.

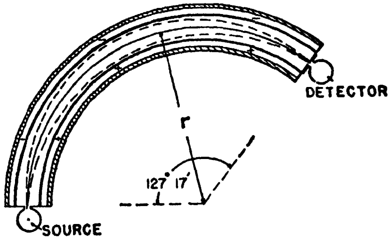

FIG. 2.15. Beta spectrometer with electrostatic focusing.

*c. Beta Ray Spectrometer with Electrostatic Focusing.* It was shown by Hughes and Rojansky [21] that by the use of a radial, inverse first-power, electrostatic field a bundle of electrons of the same energy could be focused in a manner similar to that accomplished by a magnetic field. It was calculated that for an angle of deviation equal to 127° 17′ two electrons starting through the entrance slit as shown in Figure 2.15 will refocus and pass through a receiving slit into the detector. A beta spectrometer operating on this principle has been used successfully by Backus.[22] It is particularly adaptable to the measurement of low energy particles. The inverse first-power, radial field is provided by the two concentric electrodes made as grids rather than solid plates to avoid scattering. The electrodes are spaced about one inch apart with a mean radius of six inches and the chamber is evacuated. A linear relationship exists between the energy of the particles and the voltage difference between the electrodes.

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[20] See O. Klemperer, *Phil. Mag.*, **20**, 545 (1935); and M. Deutsch, *Phys. Rev.*, **59**, 684 (1941).

[21] A. L. Hughes and V. Rojansky, *Phys. Rev.*, **34**, 284 (1925).

If the mean radius is $r$ and the outer and inner electrodes have radii $r_2$ and $r_1$, respectively, then it may be calculated for the geometry shown that the energy $W$ of the particles undergoing refocusing as shown is approximately—

✓

$$W = \frac{V_2 - V_1}{2 \log_e \left(\frac{r_2}{r_1}\right)} = 3.0(V_2 - V_1) \qquad \textbf{(2.10)}$$

In this equation $W$ is the energy of the particles in electron volts refocused by applying to the plates as shown, a potential difference $(V_2 - V_1)$ in volts. ✓

**2.11. Calorimetric Methods.** When the radiation from radioactive bodies of any kind is absorbed by matter, the temperature of the absorber is increased. This phenomenon was first demonstrated by P. Curie and A. Laborde in 1903.[23] By arranging the junctions of iron-constantan thermocouples, one in a specimen of pure barium chloride and the other in an identical specimen of "radiferous" barium chloride, a steady difference in temperature of 1.5° C. was observed. On putting one gram of the "radiferous" barium chloride in a Bunsen calorimeter they found that about 14 calories of heat were released per hour.

The amount of heat observed depends upon how completely the various radiations are absorbed. Many subsequent investigations [24] to ascribe the proper heating effect to each type of radiation have been carried out. When adjusted for a source of one gram of radium, the number of calories released per hour as reported by Rutherford for the various types of radiation, from the equilibrium products are shown in Table 2.1.

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[22] J. Backus, *Phys. Rev.*, 68, 59 (1945).

[23] P. Curie and A. Laborde, *Comptes Rendus*, 136, 673 (1903).

TABLE 2.1

| *Source* | *Alpha Rays + Recoil Atoms* | *Beta Rays* | *Gamma Rays* | *Total* |
|---|---|---|---|---|
| Radium........ | 25.2 Cals. | | | |
| Radon .......... | 29.8 | | | |
| Radium A ....... | 31.9 | | | |
| Radium B<br>Radium C ........ | 37.5 | 6.3 | 9.4 | |
| Totals........ | 124.4 | 6.3 | 9.4 | 140.1 ✓ |

The most recent experimental determinations [25] indicate that 139.6 calories are released in one hour by one gram of radium in equilibrium with its products. To liberate energy at the continuous rate of one kilowatt, 6140 grams of radium would be required.

Calorimetric measurements were made by Ellis and Wooster [26] to determine the energy of the beta radiation from radium E. This measurement was significant in the acceptance of the neutrino.

The energy of the particles derived from the fission of uranium was measured by the use of a sensitive calorimeter. It was determined in this way by Henderson [27] that the average energy per atom on fission was about 186 million electron volts.

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[24] S. Meyer and V. Hess, *Wiener Ber.*, **121**, 603 (1912); V. Hess, *Wiener Ber.*, **121**, 1 (1912); E. Rutherford and Robinson, *Phil. Mag.*, **25**, 312 (1913).

[25] S. W. Watson and M. Henderson, *Proc. Roy. Soc. A*, **118**, 318 (1928); I. Zlotowski, *Jour. Phys. Rad.*, **6**, 242 (1935).

[26] C. D. Ellis and W. Wooster, *Proc. Roy. Soc. A*, **117**, 109 (1927).

[27] M. Henderson, *Phys. Rev.*, **58**, 774 (1940).

**2.12. The Mass Spectrograph.** In determining the properties of "positive" rays, in a discharge tube, J. J. Thomson really constructed the first "mass" spectrograph. The collimated beam of particles was allowed to pass first through a magnetic field in which they received a horizontal deflection and then through an electric field giving a vertical deflection. The deflection of the particles was noted on a fluorescent screen. A beam of positive particles all with the same mass but with different velocities would spread out so as to form a parabola on the screen. Other particles with the same charge but of larger mass would appear as another parabola with smaller displacement.

If the singly charged particles all are accelerated by the same potential, then they will have a common energy. In this case the magnetic field alone will suffice to resolve the particles with respect to mass. An apparatus of this type in which the moving ions traced out semicircular paths was arranged and extensively used by Dempster.[28]

Beams of charged particles that are homogeneous electrically $\left(\frac{mv^2}{e} \text{ constant}\right)$ or homogeneous magnetically $\left(\frac{mv}{e} \text{ constant}\right)$ may be focused like a beam of light. A mathematical analysis demonstrating the possibility was carried through by Fowler,[29] and an apparatus was constructed and used by Aston. The arrangement employed is shown schematically in Figure 2.16*A* and in somewhat more detail in Figure 2.16*B*. The narrow beam of rays emerging from the cathode canal is spread into a spectrum by the electric field. After the spreading in the electric field, the rays may be regarded as emanating from a virtual point source within the plates. Now just as it is possible to take advantage of the dispersive power of glass to form an achromatic image, so may those singly charged particles of the same mass be brought together by the magnetic field *M* to a common point on the photographic plate *P*. Those particles having a slightly different mass will arrive at a different point.

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[28] A. J. Dempster, *Phys. Rev.*, **11**, 316 (1918).

[29] F. W. Aston, *Phil. Mag.*, **38**, 709 (1919); F. W. Aston and R. H. Fowler, *Phil. Mag.*, **43**, 514 (1922); F. W. Aston, *Nature*, **137**, 357, 613 (1936).

The accurate comparison of two masses in a mass spectrum depends on the determination of two quantities, the distance between the lines and the dispersion constant. The latter quantity is determined by a measurement of the interval between two lines due to masses differing by a small known amount. The hydrides of the various elements are useful to this end. It then becomes possible to investigate an unknown element by bracketing it with another known element perhaps in a different state of ionization so as to form doublets. Such doublets as ($O^+$, $Ti^{3+}$), ($N^+$, $Fe^{4+}$), ($Pd^+$, $Bi^{2+}$), etc., have been successfully used.

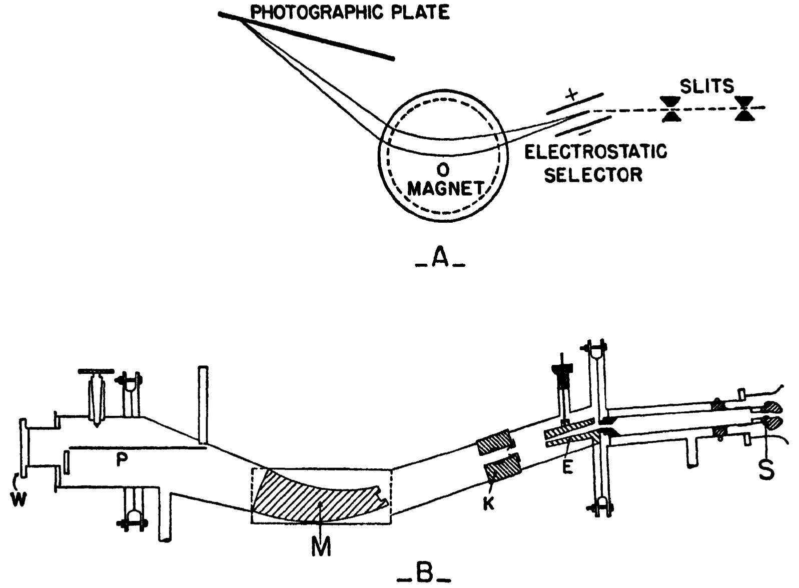

FIG. 2.16. (*A*) Schematic and (*B*) detailed sketch of mass spectrograph (Aston).

Since the excellent initial work of Aston a great number of modifications in mass spectrographs have been introduced.

Among the important contributors in this field are Dempster,[30] Bainbridge,[31] Jordan, Bleakney,[32] and Nier.[33] A sketch of the simple and effective apparatus devised by Nier is shown in Figure 2.17. It is essential that a line through the source slit and the receiving slit pass through the intersection of the two inclined surfaces limiting the magnetic field. In this case, a dispersing beam of particles of a given mass normal at the first surface will leave the second surface so as to come together at the symmetrically placed receiving slit. The angle of refraction is 60 degrees. To focus different isotopes at the collector, the accelerating voltage at $E_1$ is varied. The ions are again slowed down by a potential at $E_2$ so that no disturbing influence will arise by secondary ions at impact.

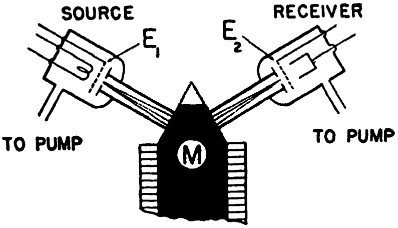

Fig. 2.17. Mass spectrograph (Nier).

## QUESTIONS AND PROBLEMS

1. The average energy of formation per pair of ions is 35 ev. A beta ray of energy 1 Mev or more produces about 25 ion pairs per cm. At 50 Kev or less about 200 ion pairs are produced per cm. Estimate the range of a 1 Mev beta particle in normal air by assuming the average ion production to be that of the mean. How will it be different in practice?

*Answer:* 253 cm, much larger.

2. An alpha particle whose energy is 5 Mev has a range in standard air of 3.51 cm. About how many ion pairs are produced during its absorption, assuming the above energy per pair? Express the total charge of one kind produced by the alpha particle in ESU and in coulombs.

*Answer:* $1.425 \times 10^5$, $6.88 \times 10^{-5}$ ESU, $2.29 \times 10^{-14}$ coulombs

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[30] A. J. Dempster, *Phys. Rev.*, **51**, 67 (1937); **53**, 64 (1938).

[31] K. T. Bainbridge and E. Jordan, *Phys. Rev.*, **49**, 883 (1936); **51**, 384 (1937).

[32] W. Bleakney and J. Hipple, *Phys. Rev.* **53**, 521 (1938).

[33] A. O. Nier, *Rev. Sci. Inst.*, **11**, 212 (1940).

**3.** A beta ray of energy 1 Mev is projected normally to a magnetic field of 800 gauss. Compute the expected radius of curvature on using the relativistic mass.

*Answer:* 5.93 cm.

**4.** The capacity of the detecting element in an ionization chamber and electrometer is only 4 micromicrofarads. The voltage sensitivity of the electrometer is 5 divisions per volt. How many ions will be required to give a deflection of one division? If the average length of alpha paths in the chamber is 3 cm, what is the effect of a single alpha particle?

*Answer:* $4.99 \times 10^6$ particles, 0.026 divisions per particle.

**5.** What mass of radium in equilibrium with its products would supply energy at the steady rate of 100 watts? What mass of normally disintegrating uranium would supply the same power?

*Answer:* 616 gms., $\sim$ 2000 tons.

**6.** If every gamma photon produces 2 ion pairs per cm along its path, how many photons must pass per $cm^2$ to be represented by an intensity of 2 roentgen units? How will this be affected by the presence of neighboring material?

*Answer:* $2.00 \times 10^9$.

## CHAPTER 3

# INDUCED RADIOACTIVITY-APPARATUS

**3.1. Early Experiments.** Shortly after the discovery of radioactivity it was noticed that any material in close contact with a radioactive substance became radioactive. This phenomenon was described in many published papers and the subject was termed "Induced Radioactivity." It was observed that the nature of the induced radioactivity in any body depended solely upon the nature of the original radioactive source and not at all upon the material receiving the activity.

With the discovery of the radioactive families, it became clear that the "induced radioactivity" was due to the arrival of a disintegration product which was itself radioactive. Thus a parent atom on disintegration might by chance result in the heavy daughter atomic residue's being projected out of the original radioactive body into the contiguous material. For example a radium atom of mass 226, will on disintegration yield a helium nucleus of mass 4 and a radon atom of mass 222. To satisfy the conservation of momentum, the velocity of the radon atom will be $\frac{2}{111}$ that of the alpha particle and hence its energy will also be $\frac{2}{111}$ as large. The energy of the alpha particle is 4.744 million electron volts, so the recoiling radon atom has an energy of 85,000 electron volts. This potential is amply sufficient if properly directed to carry the radon atom out of the parent material and into the neighboring substance.

A crystal such as diamond will, if packed in radium for some time, undergo an important change in color. The crystal will in turn be found to be radioactive and will emit the same type of radiation that characterizes radon. No physical agent will remove the radon products from the surface, showing that they have been driven in with great energy.

**3.2. Disintegration by Alpha Particles—Rutherford.** In 1914, Marsden[1] demonstrated that when hydrogen gas was bombarded by the alpha particles from radium C some of the hydrogen molecules were converted into protons and driven forward. For an elastic collision, conserving momentum and energy, it follows that a single proton would proceed forward with a velocity $v_p$ equal to $\frac{8}{5}$ the velocity of the incident alpha particle $v_a$. Its energy would therefore be $\frac{16}{25}$ that of the alpha particle. The alpha particle has a range in air of 6.97 cm or an energy of 7.75 Mev, so that the proton receives an energy of 4.96 Mev and should travel forward about 32 cm in air or 128 cm in hydrogen. Marsden found scintillations on a zinc sulphide screen placed more than 100 cm from the source of alpha particles.

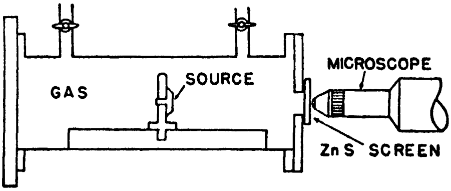

Fig. 3.1. Apparatus to detect disintegrations produced by alpha particles (Rutherford).

This investigation made use of an arrangement as shown in Figure 3.1. When the hydrogen gas in the chamber was replaced by pure nitrogen, scintillations were observed through the microscope on the screen at distances as remote as if the scintillations were made by recoil protons. On replacing the nitrogen with oxygen, under similar conditions, no scintillations whatever were observed. Observations of this sort led Rutherford[2] to suspect that the nitrogen nucleus might be disrupted by the impinging alpha particle, and might in its disintegration emit a proton. The protons were found to be emitted in all directions from the bombarded element. Such evidence confirmed the conclusions that with this simple apparatus, controlled transmutation of an element was for the first time accomplished.

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[1] E. Marsden, *Phil. Mag.*, 27, 824 (1914).
[2] E. Rutherford, *Phil. Mag.*, 37, 537 (1919).

This success with nitrogen[3] was followed by an extended investigation of all of the light elements of the periodic table. Rutherford and Chadwick[4] found evidence for the disintegration of all elements from boron to potassium with the exception of carbon and oxygen. ✓

In other laboratories similar investigations were made. Kirsch and Petterson[5] in Vienna found that carbon and several other elements, which had been reported to be inactive by the Cambridge scientists, were susceptible to disintegration. Bothe and Franz[6] obtained results more in agreement with those of Rutherford and Chadwick.

**3.3. Nuclear Cross Section.** In any interaction between a nucleus and another incident particle, it is frequently instructive to evaluate a "cross section" ($\sigma$) for the process concerned. This can be very simply visualized as follows: ✓

Each incident particle will sweep out a cylindrical volume whose area is $\sigma$ and whose length is equal to its depth of penetration. Imagine $N$ incident particles passing completely through a thin layer of thickness $t$ containing $Q$ particles per square cm. Suppose there result $n$ interactions of the type considered. The effective volume swept out by the $N$ incident particles in traversing the layer $t$ is $N\sigma t$ cm$^3$, and the average volume per nucleus in the material is $\frac{1 \times t}{Q}$ cm$^3$. Hence the number of collisions is $N\sigma t$ divided by $\frac{t}{Q}$ or

$$n = N\sigma Q, \tag{3.1}$$

and

$$\sigma = \frac{n}{NQ}\,\text{cm}^2 \tag{3.2}$$

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[3] E. Rutherford and J. Chadwick, *Phil. Mag.*, **42**, 809 (1921).

[4] E. Rutherford and J. Chadwick, *Nature*, **113**, 457 (1924).

[5] G. Kirsch and H. Petterson, *Zeits. f. Phys.*, **42**, 641 (1927).

[6] W. Bothe and H. Franz, *Zeits. f. Phys.*, **43**, 456 (1927).

It will be found in the various nuclear processes, to be considered later, that this quantity may have values ranging from $10^{-20}$ cm$^2$ to $10^{-32}$ cm$^2$. It is not inherently determined by the dimensions of the bodies and for two given particles may have different values depending upon the particular process considered. This may be used to indicate the probability of a nuclear reaction. Thus a reaction for which $\sigma$ is $10^{-24}$ is one hundred times more probable than one for which $\sigma$ is $10^{-26}$ cm$^2$. The cross section $10^{-24}$ cm$^2$ is commonly termed a "barn."

**3.4. Disintegration by Protons—Cockcroft and Walton Experiment.** With the certainty that nuclear disintegrations could be produced by alpha particles, numerous attempts were made to accelerate other ions to sufficiently high speeds to produce a similar effect. Success was first attained at Cambridge by Cockcroft and Walton [7] with the use of accelerated protons. They used a voltage multiplying circuit similar to an arrangement that had been used by T. E. Allibone to accelerate electrons. The principle of operation of the apparatus is illustrated in Figure 3.2*A*. Condensers of equal capacity are represented by $C_1$, $C_2$, $C_3$, etc. If the switch blades are in the down position, then the battery $B$ is connected across the condensers $C_1$ and $C_5$. On moving the blades to the up position, condenser $C_5$ transfers a proportional part of its charge to condenser $C_2$. On the next downward movement of the switch blades, $C_2$ transfers half of its charge to $C_6$ which in turn passes half of its charge on to $C_3$. A continuous up-and-down motion of the switch blades results in a movement of charge upward until every condenser is charged to the potential of the battery. The total over-all potential is the sum of that of the series condensers, and is applied to the discharge tube.

In the actual apparatus, as shown in Figure 3.2*B*, an alternating voltage is applied and the switching action is accomplished by the use of rectifying vacuum tubes. The first apparatus attained an output of 300,000 volts. A subsequent apparatus was designed [8] to yield energies up to 800,000 electron volts. In operation it was able to deliver a beam of protons up to 10 microamperes at 700 KV. On impact with lithium or beryllium targets, an appreciable yield of alpha particles was observed in all directions indicating nuclear disintegration.

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[7] J. D. Cockcroft and E. Walton, *Proc. Roy. Soc.*, 129, 477 (1930).

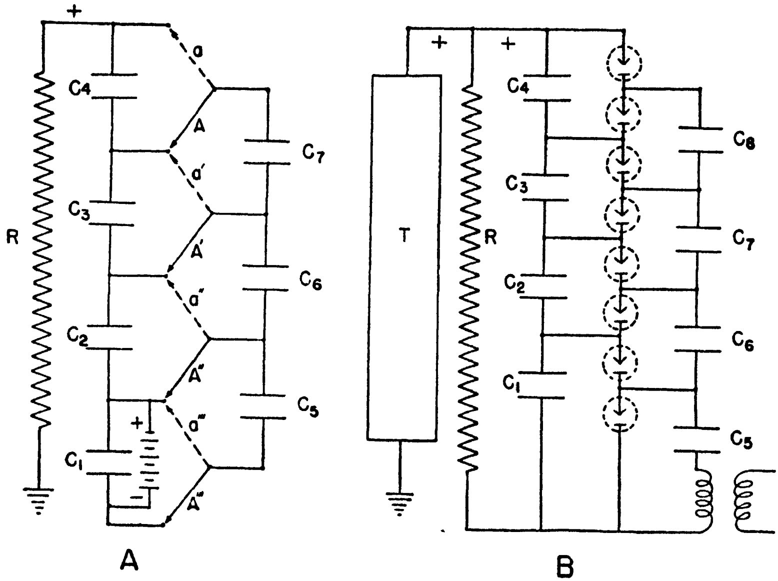

FIG. 3.2. Voltage multiplying circuit; (*A*) mechanical switching, (*B*) vacuum tube switching (Cockcroft and Walton).

In fact, with lithium, it was found that protons having energies as small as 20,000 electron volts could produce occasional disruptions.

The reaction involved was interpreted as the formation of two alpha particles from the combining of the proton and the lithium isotope of mass 7. This can be represented by an equation as

$$_1H^1 + {_3Li^7} \rightarrow {_4Be^8} \rightarrow 2{_2He^4} + Q.$$

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[8] J. D. Cockcroft and E. Walton, *Proc. Roy. Soc. A*, 136, 619 (1932).

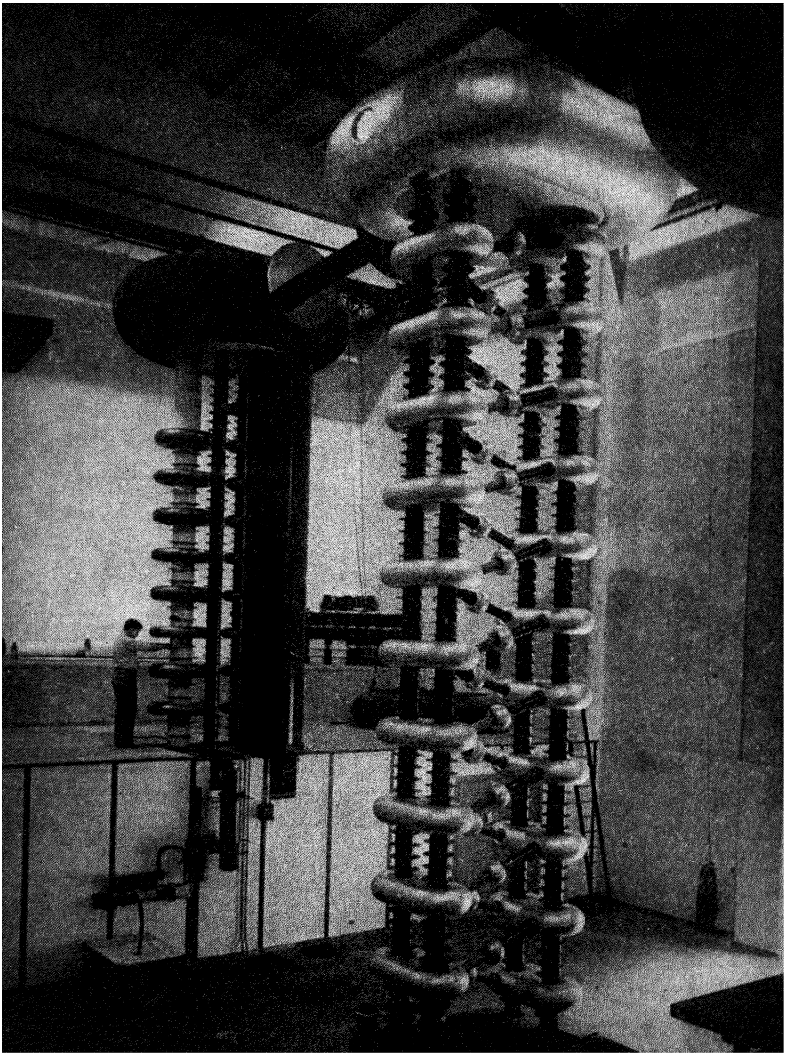

Fig. 3.3. Three million volt accelerator (Cockcroft and Walton).

The term $Q$ represents the kinetic energy of the two alpha particles in excess of the kinetic energy of the incident proton. It arises from the fact that the combined masses of proton and lithium 7 are greater than the combined mass numbers of two alpha particles by 0.01859 mass units. This mass corresponds to an energy of 17.3 million electron volts. This very large amount of energy can then occasionally be set free by as little as 20,000 electron volts or an energy magnification of 1000-fold produced. At this low bombarding energy, however, the probability that one incident particle will produce a disintegration is less than one in a million, so that no over-all gain in available energy can be anticipated from this source. Oliphant and Rutherford constructed a similar device, capable of delivering a beam of 100 microamperes of deuterons at the relatively low potential of 250 thousand volts. At this energy a high yield of neutrons was produced by bombarding ice made of heavy water.

An enlarged unit designed to deliver particles whose energy is 3 million electron volts is shown in Figure 3.3. The enormous size of the equipment is revealed by the relative magnitude of the man in the picture.

**3.5. Transformers.** On account of insulation difficulties it is not feasible to raise the secondary voltage of a transformer to indefinitely high values. By using a Tesla coil arrangement in a tank of oil under pressure, Breit, Tuve, and Dahl[9] reported the production of several million volts but no application was made of the output.

By arranging a succession of transformers each of which develops a voltage such as 200 KV and in turn excites another contiguous similar unit, an unlimited output voltage may be derived with no insulation problem greater than that for 200 KV. Figure 3.4 shows a five-stage arrangement of this sort as used by H. R. Crane,[10] with an output of one million volts.

[9] G. Breit, M. Tuve, and O. Dahl, *Phys. Rev.*, **35**, 51 (1930).
[10] H. R. Crane, *Phys. Rev.*, **52**, 11 (1937).

The output of each unit is applied to accelerating cylinders in the discharge tube. Ions are admitted and accelerated only on the positive peak of the potential wave. This arrangement was patterned after a similar installation at Pasadena constructed by Lauritsen and his associates.[11] The multistage transformer was first developed by Sorensen.[12] ✓

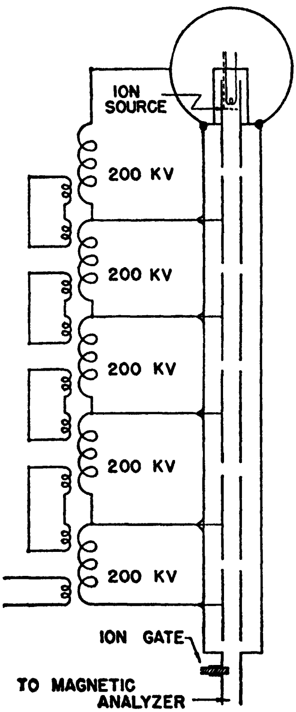

FIG. 3.4. Multistage high voltage transformer.

**3.6. Use of Atmospheric Electricity.** It is a well-known fact that at most places on the earth's surface a rather steep normal potential gradient exists. This gradient is usually of the order of 200 to 400 volts per meter, but in mountainous country, particularly during stormy weather, it may become as large as 100,000 volts per meter. In 1928 an attempt was initiated by Brasch [13] and co-workers at Mount Generoso to utilize this phenomenon in the operation of a discharge tube at extremely high potentials. A report on the project was given in 1931. The arrangement used is shown schematically in Figure 3.5*B*. The high potential pick-up terminal with its supporting insulated cable stretching from one peak across to a neighboring summit is shown in Figure 3.5*A*. By raising or lowering the grounded terminal *G* with a winch at *C* the gap between *H* and *G* could be varied as desired. For a free height of 100 meters, potential differences up to 15 million volts could be observed [14] between *G* and *H* during and both before and after a severe storm. No successful application of the high voltage was made.

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[11] C. C. Lauritsen and R. D. Bennett, *Phys. Rev.*, **32**, 850 (1928).

[12] R. W. Sorensen, *Jour. A.I.E.E.*, **44**, 373 (1925).

[13] A. Brasch and F. Lange, *Zeits. f. Phys.*, **70**, 10 (1931). C. Urban, who conducted the first experiments on atmospheric high potentials, lost his life thereby.

[14] A. Brasch, *Naturwiss.*, **21**, 82 (1933).

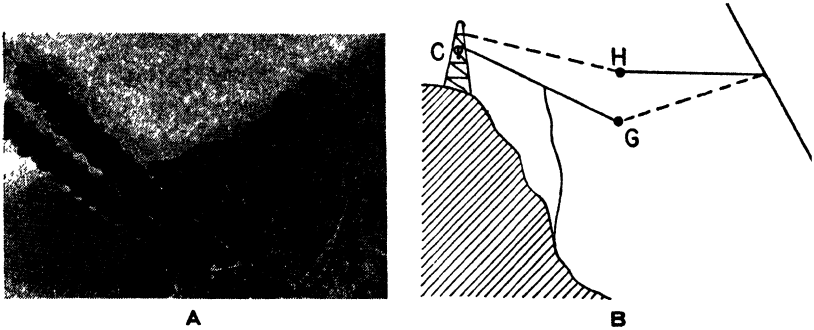

Fig. 3.5. (*A*) View of cable for high potential from atmosphere; (*B*) circuit plan.

**3.7. The Impulse Generator.** When charged condensers are connected in series, the over-all potential difference is of course the sum of the individual falls of potential. This principle has often been used as a method of voltage multiplication. The condensers can be charged in parallel and then shifted to a series connection. This same procedure has been utilized in high-potential devices known as "impulse" generators. Figure 3.6 shows an arrangement as used by Brasch and Lange[15] capa-

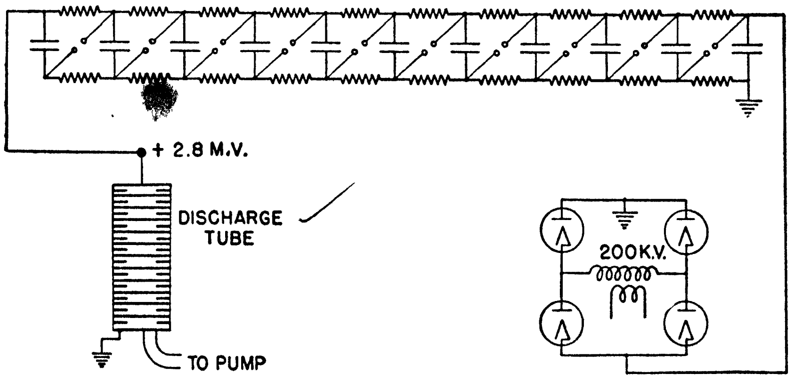

Fig. 3.6. An impulse generator for high voltage.

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[15] A. Brasch and F. Lange, *Zeits. f. Phys.*, 70, 10 (1931).

ble of developing potentials up to 2.4 million volts. A full wave rectifier supplies EMF to the condensers through the high resistances as shown.

Each spark gap is in parallel with one resistance and one condenser. When the potential across a spark gap becomes sufficiently high it breaks down. The breakdown of any one gap with its consequent lowering of resistance is immediately followed by the breakdown of all other gaps if they are properly adjusted. In this condition the circuit may be regarded as if the high-valued resistances were not present and as if the line of charged condensers are connected in series by the line of conducting spark gaps. In operation, about 2 impulses were produced per second and the output used to accelerate particles in the discharge tube shown on the left. The wall of this evacuated tube consisted of a stack of alternate conducting and insulating rings of sufficient height to withstand the voltage without external sparking.

**3.8. The Van de Graaf Generator.** Because of mutual repulsion, any electric charge communicated to a conducting body will distribute itself over the external surface. The idea of using this principle as the basis of an electrostatic generator was proposed as early as 1890 by Lord Kelvin.[16] It was forty years later before a successful working model was produced. By supplying the charge continuously at the center of an insulated metal sphere, R. J. Van de Graaf [17] in 1931, developed a high-potential generator capable of a steady output. The electric charge was sprayed onto a moving insulated belt and conveyed to the center of a large sphere mounted on a cylindrical textolite supporting post. Within the sphere the charge leaked from the moving belt onto a collector system connected to the sphere, and raised the potential accordingly. The maximum limiting potential of the sphere is determined by the breakdown electric field in the gas at the surface of the sphere, or in the supporting insulator.

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[16] John Gray, *Electrical Influence Machines*, Whittaker, London (1890).

[17] R. J. Van de Graaf, *Phys. Rev.*, 38, 1919 (1931)

Suppose the radius $r$ of a sphere is, say, 1 meter and the limiting electric field $\mathcal{E}_m$ at the surface is 30,000 volts per centimeter or 100 ESU. It follows that the limiting charge $Q_m$, the maximum potential $E_m$, and the capacity $C$ (= 100 ESU) are related as follows:

$$Q_m = CE_m = 100E_m$$

and

$$\mathcal{E}_m = 100 = \frac{Q_m}{r^2} = \frac{100E_m}{(100)^2} = \frac{E_m}{100} \tag{3.3}$$

Therefore

$$\begin{aligned} E_m &= 100 \times 100 = 10{,}000 \text{ ESU} \\ &= 3{,}000{,}000 \text{ volts} \end{aligned} \tag{3.4}$$

The first generator consisted of two spheres, each 2 feet in diameter and mounted upon neighboring insulated posts. One sphere was charged positively and the other negatively. A potential difference of 1,500,000 volts was obtained with a continuous current of 25 microamperes. Plans were then laid [18] for a similar machine with spheres 15 feet in diameter, capable of producing 20 million volts. Due to various difficulties this goal has never been reached.

The maximum electric field that can exist without breakdown goes to larger values if the pressure of the gas is increased, or, even better, if the space is completely evacuated. This indicated the possibility of higher potentials with apparatus of smaller over-all dimensions, provided a gas-tight housing surrounded the insulated charged conductor. To obtain a satisfactory vacuum, considerable difficulty would be experienced, and this procedure has not been tried. On the other hand many installations have been put into operation, in which an increased pressure is employed.

A 2.4-million-volt generator of this sort operating in a tank at a pressure of 100 pounds per square inch was constructed at Wisconsin by Herb and his associates.[19] Two additional features have been introduced allowing still higher output voltages with no increase in dimensions. A relatively small number of heavy gas molecules, such as freon ($CCl_2F_2$), will, because of their large cross section for electron capture, increase substantially the electric field needed for breakdown.

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[18] R. J. Van de Graaf, K. T. Compton, and L. C. Van Atta, *Phys. Rev.*, **43**, 149 (1933).

[19] R. G. Herb, C. Turner, C. Hudson, and R. Warren, *Phys. Rev.*, **53**, 579 (1940).

Under high pressure, air will withstand a greater potential gradient in a short gap than in a long one. Accordingly, Herb converted his generator from one with a single high-potential electrode to an arrangement of three separate concentric electrodes. Each was connected to a respective point distributed along the output resistance, so that in effect there were now three series gaps. In this way the output voltage was raised from 2.5 up to 4.5 million volts.

A compact unit capable of generating up to 4.5 million volts as developed by Dr. Van de Graaf is shown in Figure 3.7. This machine may be used to accelerate either electrons or protons. The method of spraying on and removing the negative or positive charge at the sphere is shown schematically in plan *A* and a skeletal view of the entire apparatus in view *B*. The discharge tube is usually surrounded by corona rings to distribute the potential uniformly. The accelerated electrons or protons impinge on a target, producing X-rays or nuclear disintegrations.

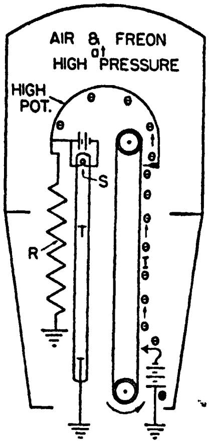

FIG. 3.7. (*A*) Plan of the Van de Graaf generator.

Many larger installations have now been constructed and put to use for accelerating heavy ions.[20] The dimensions have been chosen so that voltages up to 10 million could be expected. These voltages have not been attained, usually because of leakage along the surfaces of the insulators.

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[20] See W. H. Wells, R. Haxby, W. Stephens, and W. Shoupp, *Phys. Rev.*, 58, 162 (1940); M. A. Tuve, L. R. Hafstad, and O. Dahl, Dept. Terr. Mag. Washington, Reports (1941).

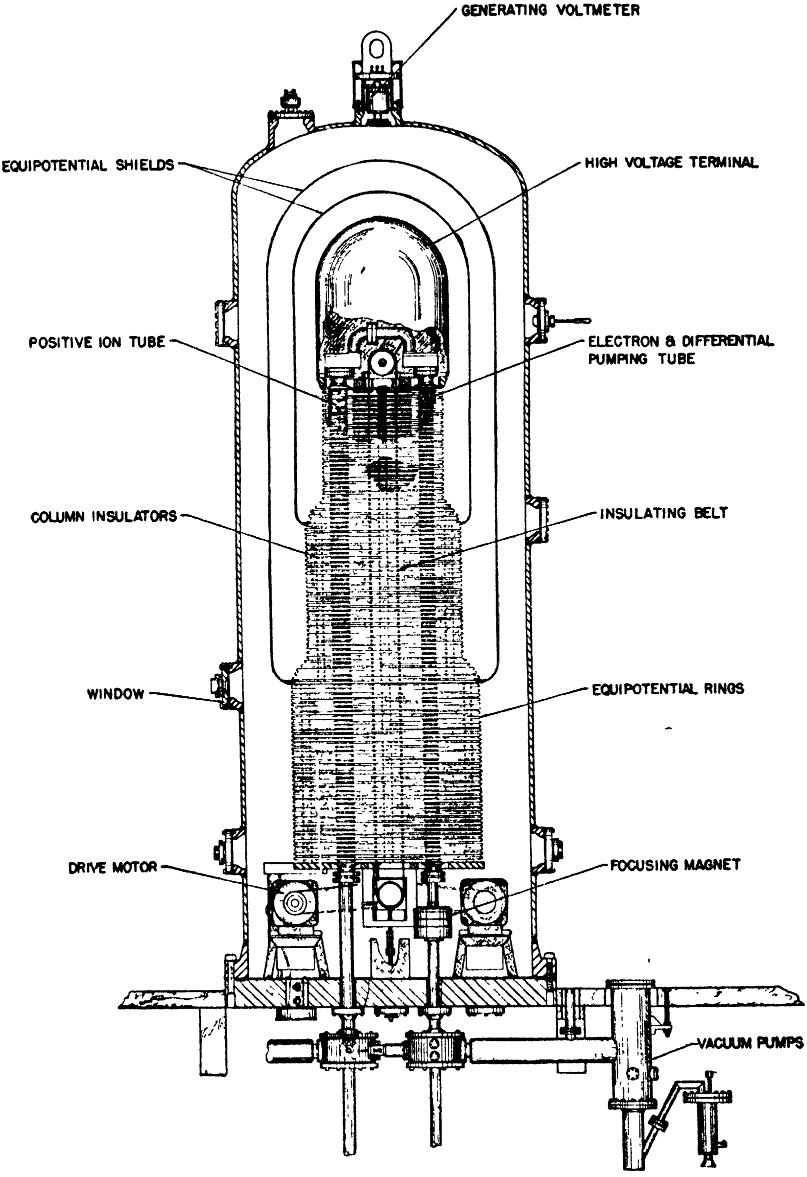

FIG. 3.7. (*B*) Skeletal view (Van de Graaf, Buechner, Woodward, McIntosh, Burrill, and Sperduto).

**3.9. The Linear Accelerator.** In 1929, R. Wideroe[21] proposed an accelerating tube in which the output voltage should be many times that of the input. The tube should be provided with a large number of hollow cylindrical electrodes of progressively increasing length all arranged along a common axis. This was called a "linear accelerator." A schematic diagram of the device is shown in Figure 3.8. A working model of the apparatus, provided with 30 accelerating electrodes, was described by Sloan and Lawrence in 1931.[22] A high-frequency generator operating at an output of 10 megacycles per second has its terminals connected to the accelerating cylinders arranged in two groups. One terminal is connected to the group consisting of electrodes numbered 1, 3, 5, etc., and the other terminal goes to the group of remaining cylinders.

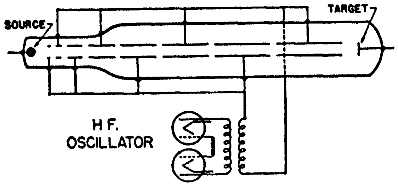

FIG. 3.8. The linear accelerator for high energy particles.

In order that ions beginning at the source *S* may be carried continuously along the tube from left to right it is necessary that the distance from the center of one cylinder to the center of the next, including the gap, be just sufficient so that the time of transit of the particle between the two points is one-half of the period of the oscillating current. For the early stages this means steps with lengths in the ratio of the square roots of successive integral numbers, since the ions gain equal increments of energy at each acceleration. At very high energies the velocity of the ions approaches the velocity of light as a limit, hence each energy increment is mainly represented by an increase in mass rather than velocity.

The output of the first arrangement was about one-tenth microampere of mercury ions at an effective voltage of 1,260,000. On increasing the input voltage from 42,000 to 79,000 and adding six more accelerating cylinders, the output energy was raised to 2,850,000 electron volts.[23]

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[21] R. Wideroe, *Arch. f. Electrotech.*, **21**, 387 (1929).

[22] D. Sloan and E. O. Lawrence, *Phys. Rev.*, **38**, 2021 (1931).

A linear accelerator with a somewhat different principle for applying the high frequency input has been described by J. Beams.[24] In this apparatus a voltage wave was sent along a loaded transmission line, connected to accelerating cylinders so that the voltage surge traveled along the tube at the same velocity as the ions.

Many suggestions have been made pointing to the possibility of potentials up to a billion volts by the use of an increased tube length and more electrodes. Each electrode could be a hollow oscillator so that by proper phasing the ion would receive its energy increment while within the hollow electrode, and then be passed into each successive electrode for additional impulses. By using higher frequencies the tube may be correspondingly shortened. Several installations are at present under construction, some using frequencies as high as $3 \times 10^9$ cycles per second. It is hoped the energy of the particles will be about a million electron volts per foot length of tube.

**3.10. The Focusing of Ions, Electrically.** It might be thought that in a long discharge tube, the beam of ions would become dispersed as the distance from the source increased. Figure 3.9 shows that this is not true. This figure shows the

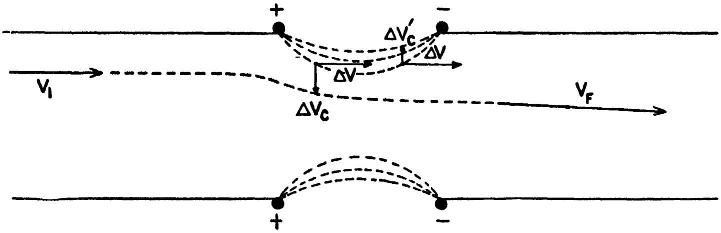

FIG. 3.9. Showing the focusing effect of the gap between charged coaxial cylinders.

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[23] D. Sloan and W. Coates, *Phys. Rev.*, 46, 539 (1934).

[24] L. Snoddy, H. Trotter, W. Ham, and J. W. Beams, *Jour. Fran. Inst.*, 223, 55 (1937); see also *Bulletin Amer. Phys. Soc.*, 21, 5 (1946).

net core. Within the tank are two hollow D-shaped electrodes as shown, supported by long copper arms whose position can be adjusted. These electrodes are called "dees" and they are connected so as to form an oscillating circuit of high frequency, usually about 12 million cycles per second.

The tank is first evacuated to as low a pressure as possible and then an appropriate gas to become the source of ions is introduced. At the center of the tank on either the floor or the ceiling is a filament maintained at a high negative potential. The column of ejected electrons from the filament will, on striking the gas, yield a column of atomic ions in the space between the dees.

In the presence of the electric field the positive ions are accelerated toward and into the negative dee. On traveling through the magnetic field they will experience a force normal to their velocity, which will result in their describing a circular path of radius $r$. The centrifugal and centripetal forces are equal. If $B$ is the magnetic induction, $e$ the electronic charge in electromagnetic units, and $m$ the mass of the ion moving at the velocity $v$, then these forces are

$$Bev = \frac{mv^2}{r}$$

so,

$$r = \frac{mv}{Be} \tag{3.5}$$

Within the hollow dee the electric field is zero and hence the ions will traverse a semicircle which will carry them around and back into the gap. Now if the time of transit for the ion in the semicircular path is equal to the time of one-half cycle of the high-frequency oscillation, then the ion arriving at the gap finds the field reversed and is again accelerated, this time into the other dee. The increased velocity results in the ion describing a new half-circle of larger radius. The success in operation depends on the important fact that the times for all half-circle transits, neglecting relativity corrections, are the same.

The time $t$ for the transit of a half-circle is the distance $\pi r$ divided by the velocity $v$. On introducing the value of $r$ from equation 3.5 it follows that

$$t = \frac{\pi r}{v} = \frac{\pi m v}{B e v} = \frac{\pi}{B}\frac{m}{e} \tag{3.6}$$

so that the radius $r$ of the orbit does not influence the time.

It is also apparent that the final energy of an ion of definite mass and charge must vary as $B^2$ and as the square of the maximum radius, because from equation 3.5

$$v^2 = B^2 r^2 \left(\frac{e}{m}\right)^2 \quad \text{and} \quad \frac{1}{2} m v^2 = \frac{m}{2} B^2 r^2 \left(\frac{e}{m}\right)^2 \tag{3.7}$$

It also follows that any change in the frequency $n$ must be compensated by a corresponding change in magnetic induction $B$ to maintain resonance, because from equation 3.6

$$n = \frac{1}{2t} = \frac{1}{2\pi}\frac{e}{m} B \tag{3.8}$$

Hence for protons, $n = 1525B$ and for alpha particles or deuterons, $n = 770B$.

In practice the accelerated ions may have such large energies that their velocity ($v$) becomes appreciable compared to the velocity of light ($c$). In this event their mass is the relativity mass $m$ which is equal to $\frac{mo}{\sqrt{1 - v^2/c^2}}$. It might be expected that this condition would make for a lack of resonance at high energies and hence place an upper limit on the output of the device.[28] This limit can be defeated by two factors. If the $m$ increases with energy, it is apparent from equation 3.8 that it is only necessary that $B$ increase accordingly, in order that $t$ be constant. This can be accomplished by a proper arrangement of the magnetic field so that it increases slightly at greater distances from the center.

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[28] M. E. Rose and H. A. Bethe, *Phys. Rev.*, 53, 206, 675 (1938).

Another factor aiding in extending the high energy upper limit is the use of a very high oscillating voltage on the dees. In this way the ions will receive a larger increment of energy each impulse and will acquire their final energy with as few round trips as possible and all disturbing factors will produce a minimum effect.

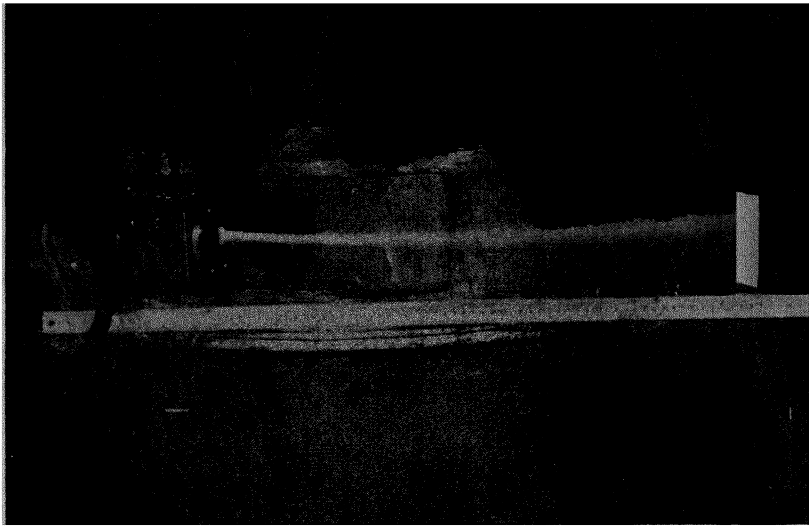

FIG. 3.11. The 10 million electron volt beam of deuterons from the Michigan cyclotron.

As the ions approach a limiting outer radius they are deviated by a deflecting plate charged to a high negative potential. This electrode is placed almost tangential to the ion path and exerts an electrostatic radial force on the ion. This force is sufficient to bring the ions completely out of the tank if desired.

The particles found to be most effective in nuclear disintegration are deuterons. These atomic ions are produced by the ionization of heavy hydrogen. Figure 3.11 shows the 10 million volt beam of deuterons produced by the Michigan cyclotron and projected into the air through a range of about 64 cm. The bluish glow in the path of the deuterons is sufficient to photograph in the dark. Under ideal adjustment the range of all deuterons will be very nearly the same. In practice it may happen that the beam is not entirely homogeneous. On using helium gas, alpha particles with a total energy twice that of the deuterons, for the same geometry, are produced.

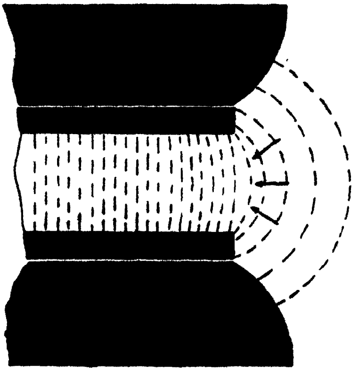

FIG. 3.12. Illustrating the focusing of ions in the cyclotron by the fringing of the magnetic field.

The ions may be kept in a median plane, as they describe their circular paths, by the proper adjustment of the magnetic field resulting in magnetic focusing. Because of the fringing at the edge, the lines of force will be bowed outward as shown in Figure 3.12. It is apparent, therefore, that an ion either above or below the median plane will experience a force directed toward the center.

Cyclotrons yielding larger and larger outputs, both in current and energy, have been constructed. These are frequently rated by the diameter of the pole pieces used. The output energy is approximately proportional to the square of the diameter. The 37-inch Berkeley cyclotron was finally able to produce deuterons of about 7 million electron volts. The later, larger machine with a 60-inch diameter is able to produce deuterons with an energy of about 20 million electron volts. At the same frequency the 184-inch machine now under construction should yield about 200 million electron volt deuterons.

Many improvements in technique have been contributed by various workers in the field. One advance, allowing much higher voltage on the dees, is a mounting and connection so that each dee with its support constitutes a quarter-wave line. This eliminates the need of glass or porcelain supporting insulators for the dees, with all the difficulties associated with their use, such as puncture or breakdown. It adds somewhat to the awkwardness of the apparatus, as the supporting arms must be much more massive, as shown by Figure 3.13*B*, which is the tank assembly of the cyclotron at the Massachusetts Institute of Technology, with the cover of the chamber[29] removed. The magnet of the same cyclotron is shown in Figure 3.13*A*.

The output of a cyclotron is not continuous but consists of pulses of ions arriving at the target. For each cycle of the alternating current two pulses would be initiated so that for 10 megacycles, 20 million ion groups would arrive at the target per second. Larger ion currents have been obtained by the use of an arc source, instead of a hot-wire filament.

Another method of defeating a limitation on maximum energy may be recognized. If the magnetic field does fall off as the radius increases and if the mass of the particle at the same time increases, then, as indicated by equation 3.6, $t$ for the outer half-circles must obviously be greater. By starting a pulse of ions at the center and slightly modulating the frequency toward lower values, the condition for resonance can be maintained for that group of particles from the center to the outer radius. The frequency now returns to the original value and a new pulse of ions is in turn escorted outward to the target. By this frequency modulation the relativity variation in mass can be effectively dealt with, but the average output current is reduced since the interval between the arrival of ion pulses is appreciable. Frequency modulation has been arranged for the 37-inch cyclotron at Berkeley by Dr. Richardson, so that it is capable of yielding protons of 15 Mev energy.

A useful nomograph relating the energy, the range, the maximum radius, the magnetic induction, and the wave-length of

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[29] M. S. Livingston, J. Buck, and R.-D. Evans, *Phys. Rev.*, 55, 1110 (1939).

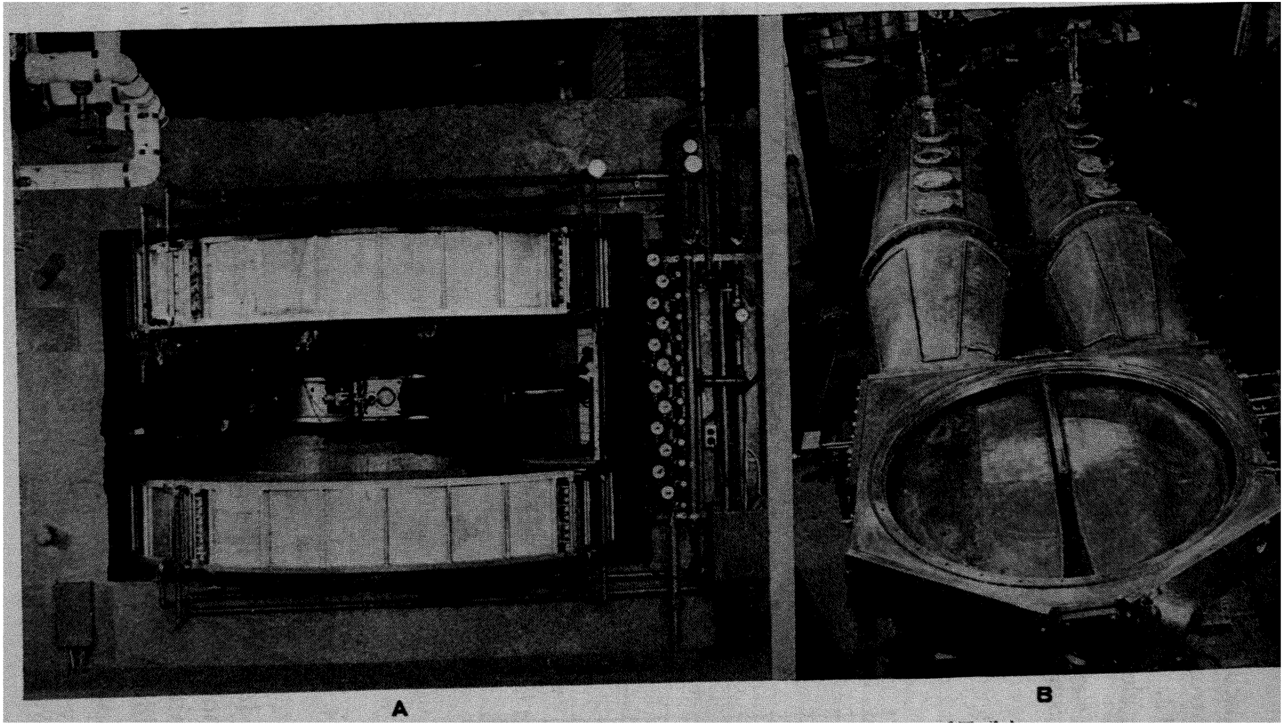

Fig. 3.13. (*A*) Cyclotron magnet; (*B*) tank assembly (Mass. Inst. of Tech.).

the oscillator for alpha particles, protons, or deuterons in the cyclotron is presented in Figure 3.14.

**3.12. The Betatron.** A device particularly suited to accelerating electrons to high potentials was first developed by D. W. Kerst in 1940.[30] The apparatus was called a "betatron" and its functioning depended upon well-known physical principles. The initial unit was able to speed up electrons to an energy of 2.3 million electron volts. This was soon followed by an enlarged unit [31] with an output of 20 million electron volts. Sub-

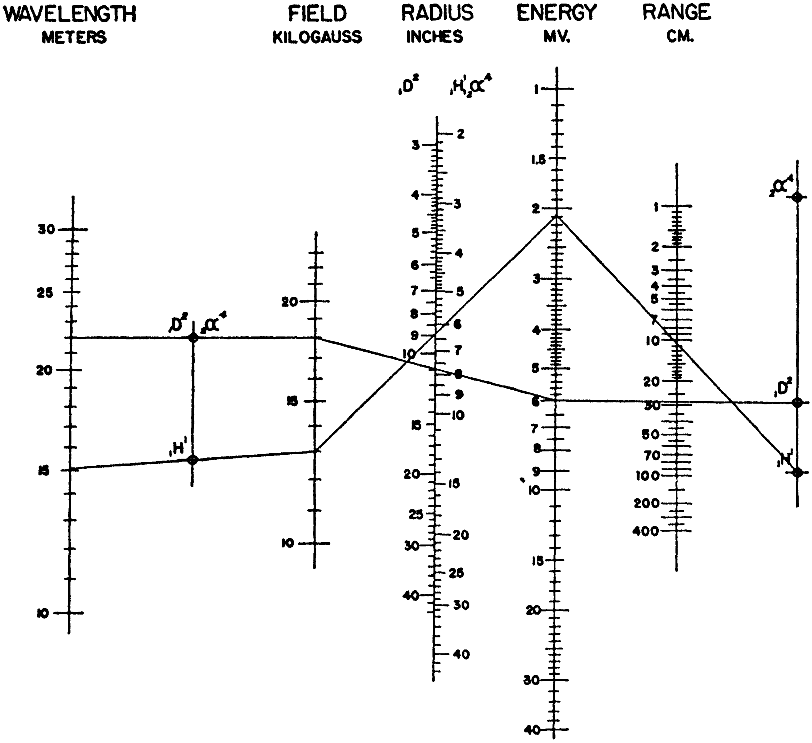

Fig. 3.14. Nomograph relating wave-length, field, and radius of cyclotron to energy and range of protons, deuterons or alpha particles.

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[30] D. W. Kerst, *Phys. Rev.*, 60, 47 (1941).
[31] D. W. Kerst, *Phys. Rev.*, 61, 93 (1942).

sequent development of a much larger instrument at the General Electric Company resulted in a 100 million volt beam of electrons.

The principle of operation may be readily understood by referring to Figure 3.15. If the magnetic flux within the circle

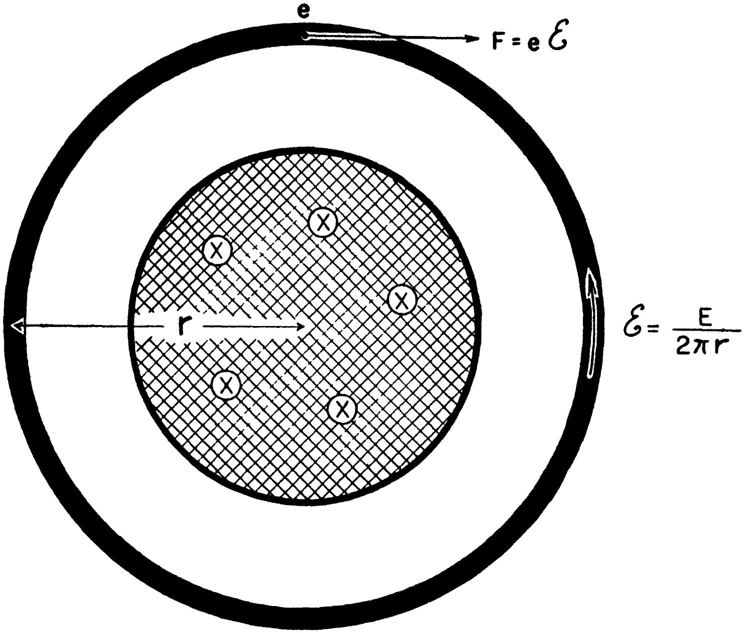

Fig. 3.15. Showing the principle of action of the betatron, magnetic flux increasing into the page.

perpendicular to the page be increased, as by bringing a north pole toward it, then any turn of wire about the circle will have an EMF induced in it, whose instantaneous value is the time rate at which the magnetic flux changes and is represented as $d\phi/dt$. This would tend to make positive electricity travel about in a counterclockwise sense, and electrons in a clockwise direction. If the electrons were in free space they would only start their clockwise transit and continue tangentially. However, if they also were traveling in a magnetic field also directed into the paper, then from the "motor" rule they would experience a central force perpendicular to their velocity. If this force were precisely the right magnitude, then the electron path would be circular. As long as the flux through the central area is increasing, so long will the EMF continue in the same sense and the faster the electron will go. Now if the magnetic induction $B$ at the electron orbit increases at the same rate as the momentum of the electron, then the path of the electron will be a circle of constant radius $r$.

The energy acquired by any charge $e$ on falling through a potential difference $E$ is $eE$. Hence, if the velocity acquired by the electron is sufficient to carry it around many trips while $E$ persists, then the final energy is the energy per turn multiplied by the number of trips. The time derivative of the flux $\phi$ is the instantaneous electromotive force in the surrounding loop and for some change from $\phi_1$ to $\phi_2$ in a time $t$, the average electromotive force $E$ is $\frac{\phi_1 - \phi_2}{t}$. For the electron at the path of radius $r$ there exists a tangential electric field $\mathcal{E} = \frac{E}{2\pi r}$ and a force $F$ equal to $\mathcal{E}e$. The acceleration $a$ of the electron of charge $e$ and mass $m$ is then

$$a = \frac{F}{m} = \frac{e\mathcal{E}}{m} = \frac{eE}{m2\pi r} = \frac{e}{m}\,\frac{\phi_2 - \phi_1}{2\pi r t} \tag{3.9}$$

A typical calculation may be carried through to note the order of magnitude of the various quantities. In the electromagnetic system imagine $\phi_2 - \phi_1 = 1{,}000{,}000$ maxwells in $\frac{1}{1000}$ sec., then for a radius of 10 cm, $E = 10$ volts and $a = 2.8 \times 10^{13}$ cm per second per second. If it were not for the increase in the mass of the electron, the velocity of the electron would have practically attained the velocity of light in the interval of $\frac{1}{1000}$ sec. In this time it would have traveled $1.4 \times 10^7$ cms or 224,000 times around. It would therefore have gained in energy 2,240,000 electron volts.

Actually, due to the increase in mass as the velocity of the electron approaches the speed of light, a condition is attained where the velocity changes only slightly with increased energy. On equating the force toward the center Bev to the centrifugal force $mv^2/r$ it follows that the momentum

$$mv = Ber \tag{3.10}$$

Hence to keep $r$ constant, any change in momentum $mv$ must be compensated by a corresponding change in $B$. Any change in momentum $\Delta(mv)$ may thus be represented as

$$\Delta(mv) = (B_2 - B_1)er \tag{3.11}$$

The same momentum change of the electron was due to an impulse from the induced electric field $\mathcal{E}$, so that

$$\Delta(mv) = Ft = \mathcal{E}et = \frac{E}{2\pi r}et = \frac{(\phi_2 - \phi_1)e}{2\pi r} \tag{3.12}$$

On equating the last terms in equations 3.12 and 3.11, it follows that

$$B_2 - B_1 = \frac{\phi_2 - \phi_1}{2\pi r^2} \tag{3.13}$$

The flux $\phi$ through the circle may be regarded as the product of the circular area and the average value of the magnetic induction $B$ within the circle. If the magnetic induction at the orbit is zero when the flux is zero then at any subsequent time the $B$ at the orbit must be just one-half of the average $B$ within the circle.

A sectional view of the accelerator is shown in Figure 3.16. By tapering the pole tips to a smaller clearance at the center, the condition of a larger average $B$ within the orbit is achieved.

The electrons are injected from a hot filament and speeded up by an accelerating field. In their transit they may spiral slightly inward or outward depending upon focusing conditions, until they reach a stable orbit. As the flux increases, the iron at the center will ultimately approach saturation. When this condition is attained equation 3.13 is no longer satisfied and the orbit tends to grow smaller. When a slightly smaller radius is reached the particle impinges upon a target, usually consisting of a thin sheet of tungsten. At this high energy the efficiency of X-ray production is very great, so that with beams so far possible, cooling the target offers no serious difficulty.

The varying magnetic field is usually achieved by applying to the large magnet, made from assembled sheet-steel laminations, an alternating current whose frequency lies between 60 and 600 cycles per second. A secondary winding on the iron core is tuned to resonance at the desired frequency by the use of a large condenser. The ions are accelerated only during one quarter of the cycle.

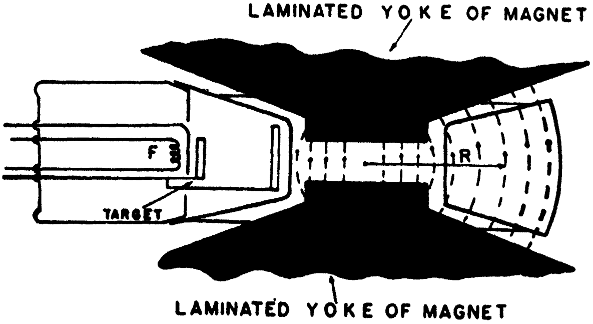

Fig. 3.16. A sectional sketch of betatron.

At the University of Illinois a unit capable of developing 250 million volts is projected. The impressive 100 Mev unit developed at the General Electric Company is shown in Figure 3.17. The huge electromagnet weighing more than 125 tons consists of over 100,000 thin pieces of silicon steel fastened together with cement. The doughnut-shaped vacuum chamber is 6 feet in diameter and its edge can be seen in the figure.

It has been shown by Kerst[32] and others that the amount of iron needed may be greatly reduced if the magnetic flux is biased to a negative value. This may be accomplished by using a relatively small number of back turns about the soft-iron pole tips, carrying a steady direct current. The change in flux, accelerating the electron, then begins at a negative value rather than at zero.

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[32] D. W. Kerst, *Phys. Rev.*, 68, 233 (1945).

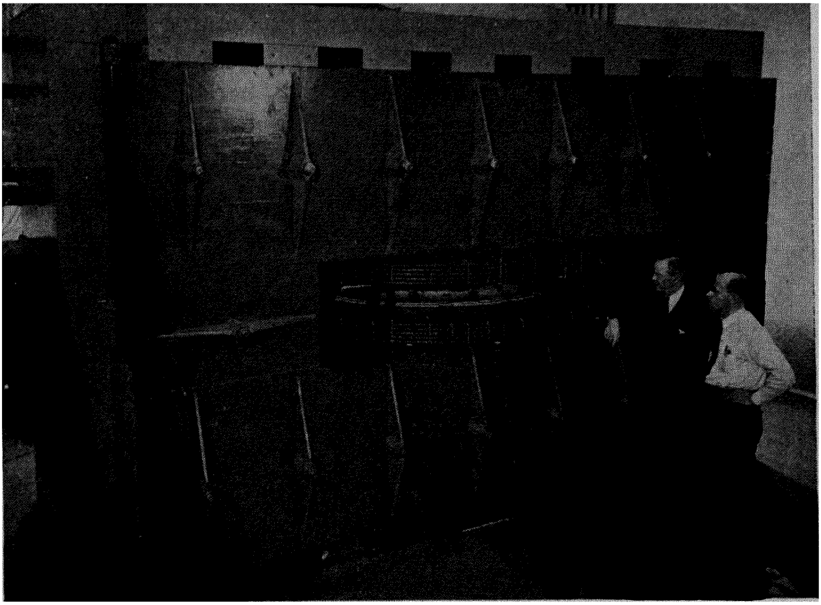

FIG. 3.17. The 100 million volt betatron at the General Electric Co.

**3.13. The Neutron Howitzer.** A mixture of radon with beryllium filings is an effective steady source of neutrons. If a beam of neutrons is desired, a collimating arrangement may be employed as shown [33] in Figure 3.18. The outer surface of the paraffin is coated with a layer of cadmium, which effectively absorbs the thermal neutrons resulting from the slowing down of fast neutrons in the paraffin.

The same type of collimation may be effectively applied in connection with the cyclotron when it is used as a source of neutrons. If high-energy deuterons are allowed to fall on either beryllium or lithium an intense emission of neutrons ensues. Such sources may be equivalent in neutron yield to that from thousands of grams of radium plus beryllium. A possible arrangement of the neutron collimator is shown in Figure 3.19. An arrangement of this sort has been described by Aebersold[34] for the 60-inch Berkeley cyclotron. The direct gamma radiation from the bombarded beryllium is absorbed by the 3-cm lead wall.

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[33] P. Powers, H. Carroll, J. R. Dunning, *Phys. Rev.*, 51, 1112 (1937); 56, 266 (1938).

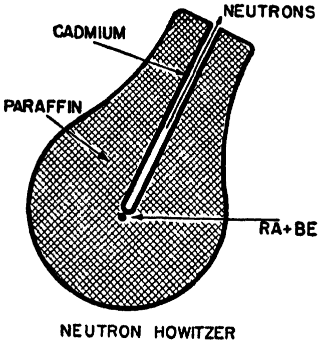

Fig. 3.18. The neutron howitzer (Dunning).

By utilizing the piles or reactors, described later under Fission, intense neutron beams may be obtained. On inserting a block of carbon through the shielding wall a column of thermal neutrons may be drawn off.

**3.14. The Synchrotron.** In the betatron the energy communicated to the electron per turn is very small, so that, in total, many turns must be made to build the energy up to an

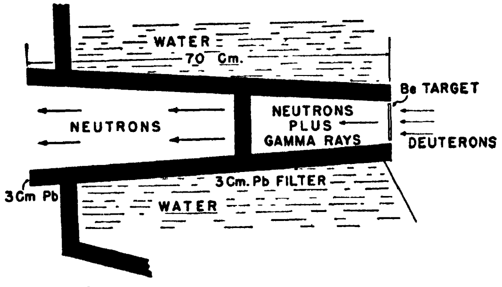

Fig. 3.19. Collimating arrangement for a beam of neutrons.

exceedingly high value. Many suggestions[35] have been made of alternative methods to achieve the same result more easily by the direct application to the particle of high-voltage impulses. The particle would still be kept in a circular path by a magnetic field. A proposed device has been described by McMillan[36] and called the "synchrotron." The multiple acceleration of the particle in a circular path is accomplished by the betatron effect together with the application of a high-frequency voltage. This voltage can be applied by allowing the particles to pass repeatedly through a cavity resonator as produced by a "klystron" oscillator or any other equivalent circuit. By varying $B$ as in the betatron, together with the application of frequency modulation, the ion is kept in a semi-stable orbit increasing only slightly in radius as the energy changes. Estimates are made that either electrons or heavy ions can be given energies up to the billion electron volt range.

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[34] P. Aebersold, *Phys. Rev.*, 55, 596 (1939).

[35] See V. Veksler, *Jour. Phys.* USSR, 9, 153 (1945).

## QUESTIONS AND PROBLEMS

**1.** The large Van de Graaf generator originally built at Round Hill consisted of two insulated spheres 15 ft. in diameter, one to be charged positively and the other negatively. Assume that the electric field can be built up to 15,000 volts per cm without serious corona loss or breakdown. Express the electrical capacity of each sphere, its maximum charge and the maximum possible potential difference between spheres.

*Answer:* 228.6 ESU, $271.3 \times 10^4$ ESU, 6.87 Mev.

**2.** The charge is carried up in each sphere by a belt 50 in. wide running at a speed of 10 ft. per second. How many electrons are carried per sq. in. of belt in the negative sphere if a current of 100 microamperes flows in a discharge tube between the two spheres?

*Answer:* $1.04 \times 10^{11}$ electrons per sq. in.

**3.** The cyclotron oscillator operates at a wave-length of 26 meters. What magnetic field would be required for resonance using (*a*) protons, (*b*) deuterons, (*c*) alpha particles, and (*d*) electrons? If the diameter of the circle of maximum radius is 44 in., what is the energy of the emergent beam in each case?

*Answer:* 7570, 15140, 15000, 4.123 gauss; 8.5, 17.3, 34, 0.0046 Mev.

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[36] E. M. McMillan, *Phys. Rev.*, **68**, 143 (1945); see also D. M. Dennison, T. Berlin and H. R. Crane, *Phys. Rev.*, **69**, 542 (1946).

**4.** If the effective voltage between duants is 40,000 volts, for cases (*a*) and (*b*) above, how far does each proton and each deuteron travel?

*Answer:* 179.5 meters, 358 meters—minimum.

**5.** In the impulse generator shown in Figure 3.6, the capacity of each individual condenser is 0.01 microfarads. A full-wave rectifier delivers the output of the transformer whose rms value is 80,000 volts at a frequency of 60 cycles per second to the bank of condensers. What is the maximum voltage across the discharge tube, and the average discharge current?

*Answer:* 1.244 million volts, 135 milamps.

**6.** In a large betatron assume that the average flux density within a circle of diameter 6 ft. changes linearly from zero up to 12,000 maxwells per sq. cm in 1/500 sec. What is the energy given to an electron each revolution at the 6-ft. diameter? What is the acceleration of the electron? How fast will it be moving at the end of the above interval, how many trips will it make, and what is its final energy?

*Answer:* 1578 ev, $48.4 \times 10^{14}$ cm per sec$^2$, $\sim 3 \times 10^{10}$ cm per sec., $1.042 \times 10^5$, 164 Mev.

## CHAPTER 4

# ALPHA RAYS

**4.1. Discovery.** By 1899 it had been shown by Becquerel and others that a strong perpendicular magnetic field could resolve the radiation from radium into two components. A deflected portion was called beta radiation and the entire undeflected part was originally termed alpha radiation. In 1900 Villard[1] found that the non-deflected component was in large measure absorbed by thin layers of material, but a smaller portion of the radiation was able to penetrate fairly thick layers. In 1903, by the use of a strong magnetic field Rutherford[2] succeeded in deflecting the easily absorbed portion of the previously non-deflected radiation but the penetrating component showed no deflection. The deflected component was bent in a direction opposite to that of the beta radiation and hence was positively charged. This beam was termed "alpha" radiation and was later shown to consist of a stream of helium ions;[3] that is, helium atoms each of which was stripped of its two orbital electrons. On collecting alpha radiation the electrons are recaptured and normal helium gas appears.

**4.2. The Specific Charge of the Alpha Particle.** The application of a field of magnetic induction $B$ to the collimated beam of alpha particles from a radium source, will result in any particle of mass $m$, charge $e$, and velocity $v$, describing a circular path of radius $r$, because of the central force $F_c$ given by—

$$F_c = \frac{mv^2}{r} = Bev \tag{4.1}$$

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[1] P. Villard, *Comptes Rendus*, **130**, 1178 (1900).
[2] E. Rutherford, *Phil. Mag.*, **5**, 177 (1903).
[3] E. Rutherford, *Phys. Zeits.*, **4**, 235 (1903).

In another observation an electric field $\mathcal{E}$ is applied so as to produce a deviation opposite to that produced by the magnetic field. On applying both fields simultaneously so that the net deflection is zero, then

$$F = Bev = \mathcal{E}e \tag{4.2}$$

Since in the magnetic deviation the charge is expressed in electromagnetic units and in the electric deflection, electrostatic units are employed, it follows that

$$v = \frac{c\mathcal{E}}{B} \tag{4.3}$$

where $c$ is the velocity of light. On substituting this value of $v$ in equation 4.1, the specific charge $e/m$ can be expressed in terms of measurable quantities as

$$\frac{e}{m} = \frac{v}{rB} = \frac{c\mathcal{E}}{rB^2} \tag{4.4}$$

This procedure has been followed in many investigations on alpha rays from various sources.[4] It was not at first recognized that the alpha particles from a source might have several velocities, and consequently it was not at once concluded that their $e/m$ was unique in value.

The first reported values, given by Rutherford, were that $e/m$ was 6300 electromagnetic units per gram and $v$ was $2.5 \times 10^9$ cms per second. It was subsequently shown, particularly on using polonium as a source, since its particles have a single velocity, that the value of $e/m$ was about 4300 in the same units. On comparing this with the corresponding value for positive rays in discharge tubes the former was found to be only half as large.

The positive rays had been assumed to be singly charged ions of hydrogen. It was therefore concluded that alpha rays were either singly charged hydrogen ions of mass 2 or doubly charged ions of helium. Since helium was generally found in radioactive ores it was reasonable to accept the latter choice. The best experimental value for $e/m$ for alpha particles up to 1928 appears[5] to be 4813 electromagnetic units of charge per gram.

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[4] E. Rutherford, *Phys. Zeits.*, 4, 235 (1902); T. des Coudrés, *Phys. Zeits.*, 4, 483 (1903); A. S. McKenzie, *Phil. Mag.*, 10, 538 (1905); E. Rutherford and T. Royds, *Phil. Mag.*, 17, 281 (1909).

Using the most recent values for the electronic charge and the mass of the helium atom, Birge[6] computes the specific charge to be 4822.3 ± .05 in the same units.

**4.3. Range of Alpha Particles.** Early experiments showed that alpha rays were readily absorbed by thin layers of materials. Even in gases their range was only a few centimeters. Unlike most other radiations their absorption in matter does not follow the exponential law. It was suggested by W. H. Bragg[7] in 1904 that the ionization along the path could be expressed as proportional to $\sqrt{r + c}$ where $r$ is the number of centimeters from the end of the range and $c$ is a constant equal to 1.33. It was later shown that this apparent decrease in ionization along the path was due to the fact that from radium there were several groups of particles, each with a different range. In any one range, theoretically, no particles were lost until the full thickness was traversed. This peculiarity in absorption would be expected if the heavy helium ions initially were all of the same energy and in passing through matter produced a trail of ions. The ions produced consist of electrons detached from the neutral atoms of gas, and an equal number of positive ion residues. Each ion-pair formed in air represents about 35 electron volts loss in energy to the alpha particle. The energy lost and the ionization produced are not exactly proportional. This is due to the fact that the ions produced possess varying amounts of kinetic energy, and some electrons are merely lifted to metastable levels producing excited but not ionized atoms. The mass of the alpha particle is about 7440 times that of the electron; hence, in collision of the two, the alpha particle loses little momentum.

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[5] E. Rutherford and H. Robinson, *Phil. Mag.*, **28**, 552 (1914); G. H. Briggs, *Proc. Roy. Soc. A*, **118**, 549 (1928).

[6] R. T. Birge, *Rev. Mod. Phys.*, **13**, 233 (1941).

[7] W. H. Bragg, *Phil. Mag.*, **8**, 719 (1904); **13**, 333 (1907).

The number of ions formed per centimeter of path, often called the "specific ionization," is found to be a function of the velocity. In general, the slower the velocity the greater the specific ionization, as if the longer the time the alpha particle spends in passing a group of atoms the greater is its chance of creating ions. The variation in specific ionization in air under standard conditions, produced by the alpha rays from polonium and from radium C′ is shown [8] in Figure 4.1. By taking the ionization about 5 mm from the end of the range as 1.0, then the initial ionization is only about 0.42. Occasionally an alpha particle suffers an impact with a nucleus and then it is likely to suffer a sudden refraction. This is an event with a low probability of occurrence.

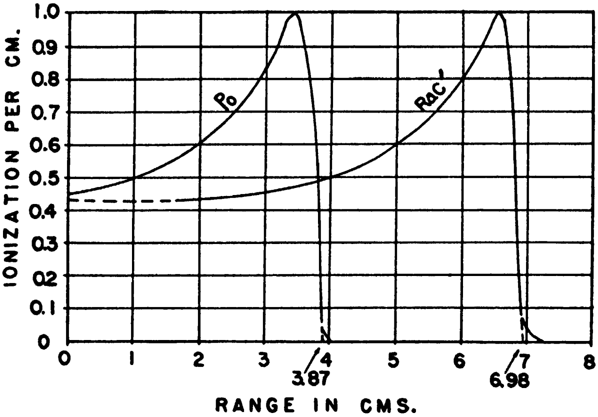

FIG. 4.1. The variation in specific ionization along the path of alpha particles from polonium and from radium C′.

An alpha particle having spent all its energy comes to the end of its course. Since all particles in a group have initially

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[8] G. H. Henderson, *Phil. Mag.*, 42, 538 (1921); I. Curie and F. Behounek, *Jour. de Phys.*, 7, 125 (1926); I. Curie and F. Joliot, *Comptes Rendus*, 187, 43 (1928).

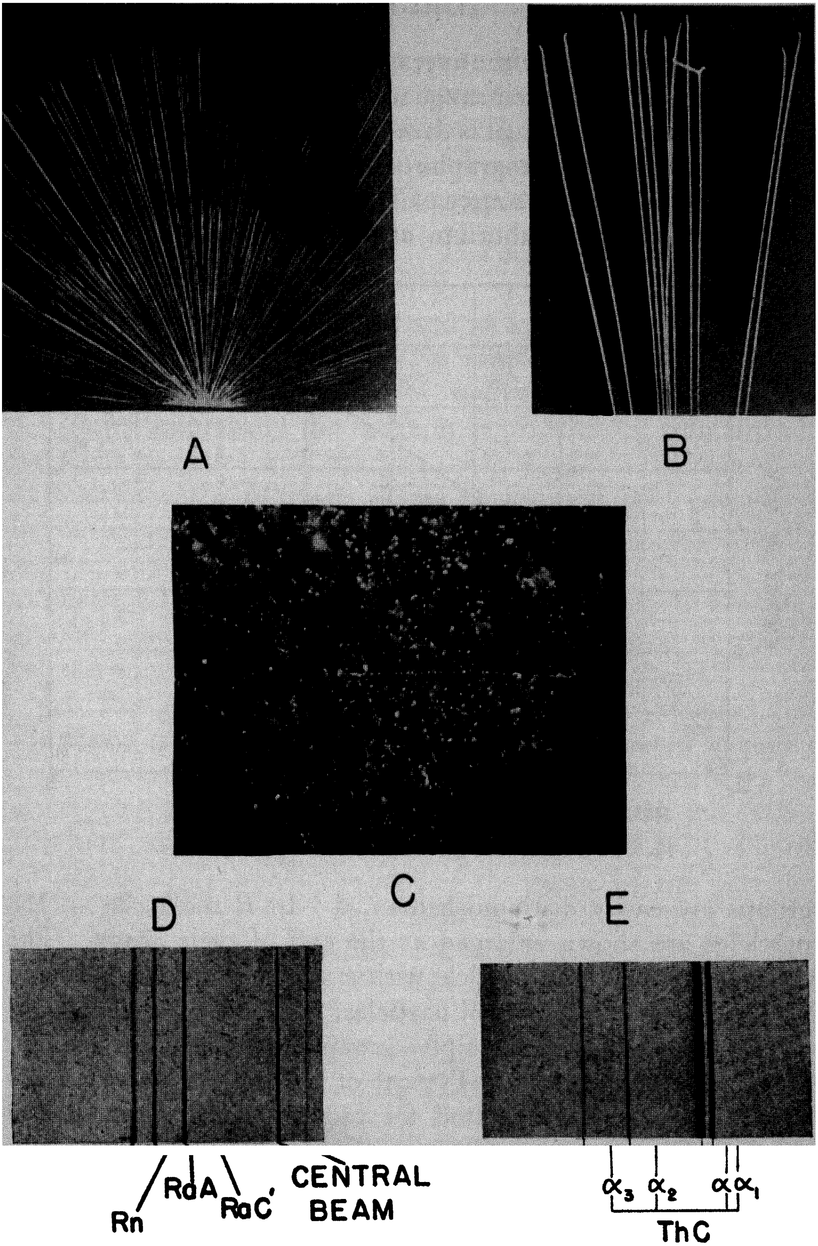

FIG. 4.2. The photographic registration of alpha particles; (*A*) alpha rays from Th(C + C′); (*B*) same, enlarged at end of range; (*C*) emulsion track of alpha; (*D*) spectrum of alpha rays from radium; and (*E*) same, from thorium C.

the same energy and on the average produce the same ionization per centimeter, then their range will be the same. This approximate uniformity in range is demonstrated in Figure 4.2, *A* and *B*. These are the photographs of cloud tracks produced by the alpha radiation from a source of Th(C + C′). The two ranges of the particles from thorium are 4.78 and 8.62 cms and the groups are easily distinguished in *A*. In *B* the paths of the particles are shown enlarged at the end of their range. The collision of one alpha particle with a nitrogen atom is revealed by the tracks of both recoil particles.

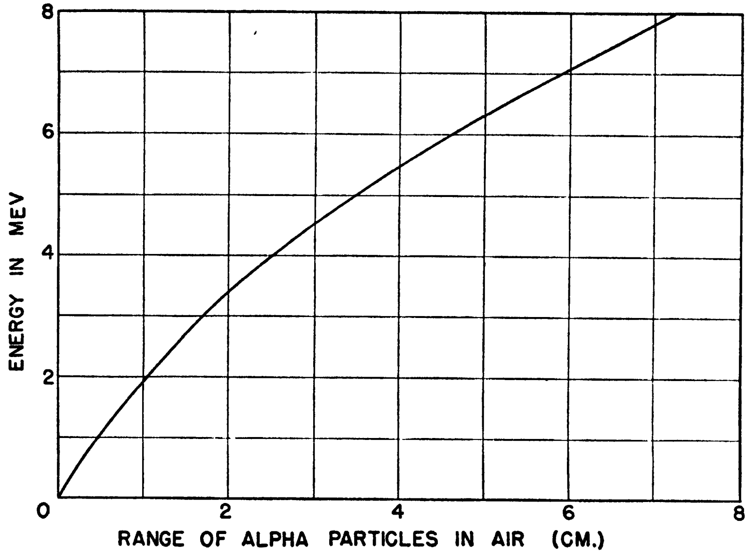

FIG. 4.3. Range-energy relationship for alpha particles.

The ranges of various alpha groups have been the subject of many investigations. Typical of the results obtained are those of Geiger,[9] who found for radium C, thorium C, and thorium C′ respectively, ranges of 6.608 cm, 4.538 cm and 8.168 cm in air under standard conditions. For ranges between 3 cm and 8 cm a relationship known as Geiger's law states that range $R$ varies directly as the cube of the velocity $v$. Since the kinetic energy $W$ varies directly as the square of the velocity, then the range varies directly as the $\frac{3}{2}$ power of the energy. This may be represented by an equation as

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[9] H. Geiger, *Zeits. f. Phys.*, 8, 45 (1921).

$$R = av^3 = bW^{3/2} \tag{4.5}$$

where $a$ and $b$ are constants. The numerical value of $a$ is found to be about $9.67 \times 10^{-28}$. At greater velocities the range varies more nearly as $v^4$ and at lower energies the range varies almost directly as $v^{1.5}$. No simple formula satisfies the range velocity relationship for unlimited energies. Figure 4.3 shows graphically the range in centimeters of standard air for alpha particles with energies up to 8 million electron volts as determined by Mano.[10] These ranges have been calculated by Bethe and Bloch [11] and the curve has been experimentally verified and extended by Holloway and Livingston.[12]

Figure 4.2*C* shows the path of an alpha particle in a photographic emulsion. The energy may be determined by counting the number of activated grains comprising the path.

**4.4. The Straggling of Alpha Rays.** It at first appeared that the alpha rays from a particular source terminated abruptly after traversing a certain definite thickness of absorber. On attempting to express this thickness precisely, the true value appeared slightly uncertain. This is illustrated by Figure 4.4 which represents [13] the end of the range of the particles from radium C′ in air. This result was obtained by a careful study of the alpha tracks observed in a Wilson cloud chamber. An explanation of the effect had already been proposed by Darwin [14] and by Bohr.[15] The path-lengths of the alpha particles in a monoenergetic group will be arranged about a most probable value according to the Gaussian law of errors.

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[10] G. Mano, *Jour. de Phys.*, 5, 628 (1934).

[11] H. Bethe and F. Bloch, *Ann. de Phys.*, 16.3, 285 (1933).

[12] M. Holloway and M. S. Livingston, *Phys. Rev.*, 54, 18 (1938).

[13] I. Curie and P. Mercier, *Jour. de Phys.*, 7, 289 (1926); L. Meitner and K. Freitag, *Zeits. f. Phys.*, 37, 481 (1926).

[14] C. G. Darwin, *Phil. Mag.*, 23, 901 (1912).

[15] N. Bohr, *Phil. Mag.*, 30, 531 (1915); L. Flamm, *Wiener Ber.*, 124, 597 (1915).

The amount of variation or straggling depends upon the process involved in the energy loss. Such calculations were made for radium C′ in air involving all possible transfers and indicated a spread of ±0.09 cm in the range as shown. The true range would therefore in this case not be the observed maximum, 6.96 cm, but rather the corrected value 6.87 cms.

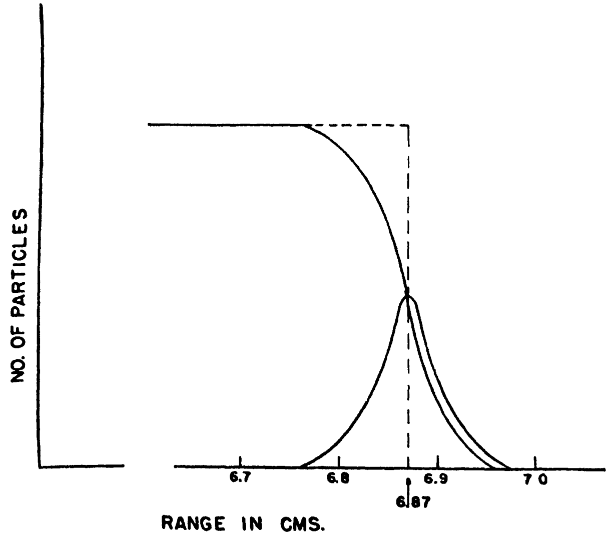

Fig. 4.4. Showing the straggling of alpha particles at the end of their range.

Similarly the number of alpha particles arriving at any detector per second will fluctuate with time. The total number observed in any second may be more or less than the average value by an amount expressed as a fluctuation. To reduce errors due to this fluctuation a large number of observations $N$ are noted. The result, together with the uncertainty, is expressible as $N \pm \sqrt{N}$. Thus if 10,000 particles are counted, the error due to fluctuations is of the order of 1%.

**4.5. Range and Half-life.** In 1911, Geiger and Nuttall[16] arrived at an interesting conclusion relating the half-life of an alpha emitter and the energy or range of its alpha particles.

[16] H. Geiger and J. M. Nuttall, *Phil. Mag.*, **22**, 613 (1911).

The element under study was placed at the center of a hollow glass sphere whose inner surface was silvered with a conducting layer and connected to a high potential. The active substance at the center was on a small disk which was connected to an electrometer. The ionization current was observed as a function of the gas pressure. The ionization was found to increase as the pressure increased up to a certain critical value at which the alpha radiation no longer reached the surface. At higher pressures the ionization current remains constant.

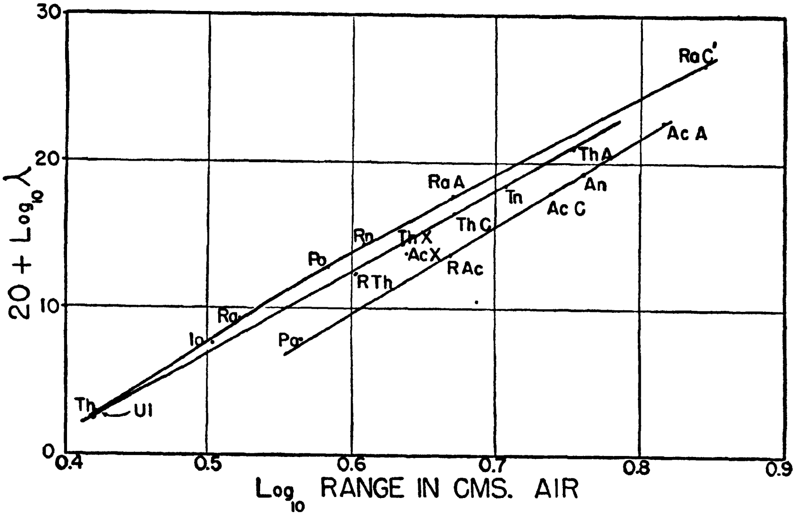

Fig. 4.5. The Geiger-Nuttall curves for the radioactive families.

It was found that if the logarithm of the range in centimeters was plotted versus the logarithm of the disintegration constant, $\lambda$ in $\sec^{-1}$ then for a particular family such as the uranium-radium family the points lie on a straight line.

Similar linear relationships are found to represent the thorium and the actinium radioactive series. The three curves at their upper ends are nearly parallel as shown in Figure 4.5 and each is represented by an equation of the form

$$\log R = a + b \log \lambda \tag{4.6}$$

The constant *b* is the same value, namely 0.0174, for the straight portion of each curve. The curves differ in the intercepts *a* on the *y* axis. Among the exceptions to the general rule are actinium X and UI.

For samarium, the range in air of 1.16 cms has been observed. This is the shortest range for any of the natural emitters and corresponds to the half-life of $1.7 \times 10^{11}$ years or a disintegration constant $\lambda$ of $1.29 \times 10^{-19}$ $\text{sec}^{-1}$. The half-life of any element emitting alpha particles of range less than a centimeter would be so long that it would be regarded as stable.

**4.6. Alpha Ray Spectra.** W. H. Bragg very early found from ionization measurements that there were four groups of alpha particles emitted by a source of radium. It was not until 1930 that precise measurements were made on these alpha spectra. At that time Rosenblum[17] examined a number of radioactive elements by means of a magnetic spectrometer with semicircular focusing. Several emitters were each found to send out only a single monoenergetic group of alpha particles. Another list of elements had spectra consisting of two or three distinct energies. A few elements, such as radium C′, thorium C, and radioactinium, each emit several discrete energy groups. The resolved spectra obtained with a source of radium are shown in Figure 4.2*D* and those from a source of Th C are shown in Figure 4.2*E*. The most energetic ray lies on the right in each case and is the least deflected. The intensities for the four lines from Th C left to right are about as 1.1:1.8:70:27, and the energies vary from 5.6 to 6.0 Mev.

The accuracy of these measurements has been somewhat improved in recent investigations.[18, 19] A summary of the known alpha ray spectra is given in Table 4.1, showing the source, the range in air, the energy in Mev and the half-life of each. These alpha energies, when combined with the gamma

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[17] S. Rosenblum, *Jour. de Phys.*, **1**, 438 (1930).

[18] M. Holloway and M. S. Livingston, *Phys. Rev.*, **54**, 18 (1938); W. V. Chang and S. Rosenblum, *Phys. Rev.*, **67**, 225 (1945).

[19] W. V. Chang, *Phys. Rev.*, **67**, 267 (1945).

TABLE 4.1. ALPHA RAY SPECTRA

| *Source* | *Range in Cm* | *Energy in Mev* | *Half-Life* |
|---|---|---|---|
| Uranium I | 2.653 | 4.20 | $4.5 \times 10^9$ *Y* |
| Uranium II | 3.211 | 4.75 | $2.7 \times 10^5$ *Y* |
| Ionium | 3.12 | 4.66 | $8.3 \times 10^4$ *Y* |
| Radium | 3.29 | 4.791 | 1550 *Y* |
|  | 3.11 | 4.620 |  |
| Radon | 4.051 | 5.4860 | 3.82 *D* |
| Radium A | 4.657 | 5.9981 | 3.05 *M* |
| Radium C | 4.06 | 5.502 | 19.7 *M* |
|  | 3.99 | 5.010 |  |
| Radium C′ | 11.580 | 10.5379 | $1.5 \times 10^{-4}$ *S* |
|  | 11.510 | 10.5052 |  |
|  | 9.724 | 9.4877 |  |
|  | 9.040 | 9.0655 |  |
|  | 7.792 | 8.2769 |  |
|  | 6.907 | 7.6802 |  |
| Radium F | 3.842 | 5.2984 | 140 *D* |
| (Polonium) see Table 4.2 |  |  |  |
| Thorium | 2.83 | 4.330 | $1.4 \times 10^{10}$ *Y* |
| Radio Th | 3.970 | 5.418 | 1.9 *Y* |
|  | 3.880 | 5.335 |  |
| Thorium X | 4.290 | 5.6825 | 3.64 *D* |
| Thoron | 5.004 | 6.2818 | 54.5 *S* |
| Thorium A | 5.638 | 6.7744 | 0.14 *S* |
| Thorium C | 4.730 | 6.0537 | 60.5 *M* |
| Thorium C′ | 11.578 | 10.5360 | $10^{-9}$ *S* |
|  | 9.740 | 9.508 |  |
|  | 8.568 | 8.7759 |  |
| Actinium U | 3.211 | 4.52 | $7 \times 10^8$ *Y* |
| Protactinium | 3.60 | 5.049 | $3.2 \times 10^4$ *Y* |
| Radio Ac | 4.72 | 6.051 | 18.9 *D* |
|  | to | to |  |
| (11 lines) | 4.27 | 5.674 |  |
| Actinium X | 4.32 | 5.719 | 11.2 *D* |
| Actinon | 5.692 | 6.8235 | 3.92 *S* |
|  | 5.240 | 6.470 |  |
| Actinium A | 6.457 | 7.380 | $2 \times 10^{-3}$ *S* |
| Actinium C | 5.429 | 6.618 | 2.16 *M* |
|  | 4.984 | 6.272 |  |
| Actinium C′ | 6.555 | 7.434 | $5 \times 10^{-3}$ *S* |

ray energies associated with the same element, are sometimes sufficient to construct an energy-level diagram for the nucleus. On greater resolution it will undoubtedly be found that the alpha spectra are much more complicated than had been anticipated. For example, polonium had been regarded as emitting a single group of alpha particles whose energy was 5.300 Mev. On using the Princeton cyclotron as a spectrometer, Chang has shown that there are at least twelve lines of lesser intensity present as shown in Table 4.2 and probably several more at still lower energies.

TABLE 4.2. POLONIUM ALPHA RAYS

| *Mev* | *Intensity* | *Mev* | *Intensity* |
|---|---|---|---|
| 5.303 | 100,000 | 4.449 | 12 |
| 5.113 | 25 | 4.303 | 7 |
| 5.065 | 25 | 4.111 | 7 |
| 4.901 | 15 | 4.016 | 5 |
| 4.838 | 11 | 3.890 | 4 |
| 4.749 | 13 | 3.685 | 4 |
| 4.640 | 10 | | |

**4.7. Stopping Power.** The density of air is 0.00129 gms. per cm$^3$ and that of aluminum is 2.699. Thus it might be expected that $\frac{1}{2100}$ cm of aluminum would be equivalent in stopping power to 1 cm of air. Actually it takes a somewhat thicker layer of aluminum, namely $\frac{1}{1700}$ cm, to be equivalent to 1 cm of air under standard conditions. Thus the stopping power of aluminum is spoken of as 1700. The stopping power is thus defined as the reciprocal of that thickness of substance equivalent to 1 cm of air, in its ability to stop alpha radiation. If the stopping power of an element be divided by the number of atoms per cubic centimeter, the quotient is termed the atomic stopping power of the substance.

The stopping is done by electrons and if each electron functions equally effectively, then it might be expected that the atomic stopping power $S$ divided by the atomic number $Z$, should be a constant. This could be termed the stopping power per electron. Actually this is found to be not the case. In the heavier elements a large share of the electrons are tightly bound in inner orbits so that they play a lesser part in ionization and the consequent slowing down of the alpha rays. It was observed by Bragg[20] that for most elements the atomic stopping power $S$ varied directly as the square root of the

TABLE 4.3. THE ATOMIC STOPPING POWER OF THE ELEMENTS

| *Element* | $Z$ | $A$ | *Atomic Stopping Power* ($S$) | $SA^{-1/2}$ | $SZ^{-2/3}$ |
|---|---|---|---|---|---|
| H | 1 | 1.00 | 0.200 | 0.20 | 0.20 |
| Li | 3 | 6.94 | 0.519 | 0.20 | 0.25 |
| Be | 4 | 9.02 | 0.750 | 0.25 | 0.29 |
| C | 6 | 12.01 | 0.814 | 0.25 | 0.25 |
| N | 7 | 14.00 | 0.939 | 0.25 | 0.25 |
| O | 8 | 16.00 | 1.000 | 0.25 | 0.25 |
| Mg | 12 | 24.32 | 1.23 | 0.25 | 0.24 |
| Al | 13 | 26.97 | 1.27 | 0.24 | 0.23 |
| Si | 14 | 28.06 | 1.23 | 0.23 | 0.22 |
| Cl | 17 | 35.46 | 1.76 | 0.29 | 0.26 |
| Fe | 26 | 55.85 | 1.96 | 0.26 | 0.23 |
| Ni | 28 | 58.69 | 1.89 | 0.25 | 0.21 |
| Cu | 29 | 63.57 | 2.00 | 0.25 | 0.22 |
| Zn | 30 | 65.38 | 2.05 | 0.25 | 0.22 |
| Ag | 47 | 107.88 | 2.74 | 0.26 | 0.21 |
| Cd | 48 | 112.41 | 2.75 | 0.26 | 0.21 |
| Sn | 50 | 118.70 | 2.86 | 0.26 | 0.21 |
| Pt | 78 | 195.23 | 3.64 | 0.26 | 0.20 |
| Au | 79 | 197.20 | 3.73 | 0.27 | 0.20 |
| Pb | 82 | 207.21 | 3.86 | 0.27 | 0.20 |

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[20] W. H. Bragg and R. Kleeman, *Phil. Mag.*, 10, 318 (1905).

atomic weight ($A$). Glasson[21] found that it equally well could be regarded as varying as $Z^{2/3}$ where $Z$ is the atomic number of the element. These values of the atomic stopping power for a few elements are shown in Table 4.3. The atomic stopping power of oxygen is taken as unity. It is remarkable that such simple relationships fit the data so well.

**4.8. Scattering of Alpha Particles.** The alpha particles were at first considered to travel in straight undeviated lines through matter. More careful observation showed that a portion of the original beam was in general deviated through small angles depending upon the thickness of the layer of material and its atomic number. The greater the atomic number of the matter and the less the velocity of the alpha particle, the greater is the average deviation. In these experiments a few particles are occasionally found whose deflection may be as much as 90° or more. Thus for Ra C′ about one particle in every 8000 suffers such a large deflection in passing through a very thin layer of gold.[22] These particles have undoubtedly come very close to an atomic nucleus so that an interaction occurred in which they suffered a large change in momentum.

From X-ray studies of crystal structure the diameter of atoms is established as being of the order of $3 \times 10^{-8}$ cms. The diameter of the nucleus, possessing most of the mass, is only a very small fraction of this. An estimate of the nuclear dimensions could be made from a careful observation of these scattered particles. It had initially been considered that these large deflections must be due to multiple encounters since it was currently thought that the electric field within the atom could not be of sufficient intensity to deflect such a heavy body as the alpha particle in a single encounter. Rutherford[23] showed that they must be due to a single encounter, as the probability of one particle already largely deflected having a second encounter of the same sort was very small. Rutherford

[21] J. L. Glasson, *Phil. Mag.*, **43**, 477 (1922).

[22] H. Geiger and E. Marsden, *Proc. Roy. Soc.*, **82**, 495 (1909); *Phil. Mag.*, **25**, 604 (1913).

[23] E. Rutherford, *Phil. Mag.*, **21**, 699 (1911).

was first to postulate that the total positive charge of the atom was concentrated in a small nuclear volume and that the equal negative charge was distributed over the much larger domain, occupied by the atom. For all deflections greater than about a degree, only the central positive charge need be considered and it was assumed to be concentrated in a minute volume as a point. The force between the positive nucleus and the positive alpha particle was considered to be a simple coulomb repulsion. On considering the heavy nucleus with a charge $Ze$ to remain at rest during the collision, the path of the $\alpha$ particle will be a hyperbola whose external focus is the scattering nucleus as shown in Figure 4.6. The distance of nearest approach $b$ will be a minimum for an alpha particle striking the nucleus directly, and in this case the alpha particle will be scattered through an angle of 180°. By equating the original kinetic energy of the alpha particle to the potential energy, as the positive charge $2e$ approaches the nuclear charge $Ze$, and is brought to a stop at the distance $b$,

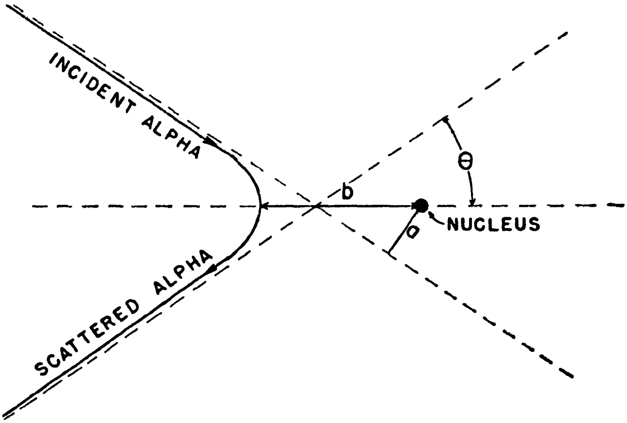

FIG. 4.6. The scattering of an alpha particle by a nucleus.

$$\frac{1}{2} m_\alpha v_\alpha^2 = \frac{2eZe}{b} \quad \text{or} \quad b = \frac{4Ze^2}{m_\alpha v_\alpha^2} \tag{4.7}$$

Rutherford showed that if $Q$ is the total number of incident particles falling normally on a thin scatterer of thickness $t$, and if $n$ is the number of atoms per cm$^3$ in the scatterer, then the number of particles $N$ arriving at a fixed receiver at a distance $r$ centimeters from the scatter along an angle $\phi$ to the original direction would be given by the following equation:

$$N = \frac{Qntb^2 \operatorname{cosec}^4 \phi/2}{16r^2} \tag{4.8}$$

This equation could be checked experimentally, term by term, by allowing a single factor to vary at a time. Geiger and Marsden[24] were the first to deal with this problem. Alpha rays from a radon source were allowed to fall normally on a scatterer consisting of an extremely thin foil of gold, placed directly on the axis of a spectrometer. The value of $N$ was noted at scattering angles $\phi$ varying from 150° down to 15°, by rotating an arm carrying a small zinc sulphide screen with accompanying microscope. The quotient $\dfrac{N}{\operatorname{cosec}^4 \phi/2}$ was found to be essentially a constant. It varied only from about 28 to 38, being greater at the smaller angle. Similarly, at a fixed angle it was noted that $N$ varied inversely as the square of the energy of the incident alpha particles, as would be expected from equation 4.8 since $b^2$ is in the numerator, and $b$ varies inversely with the energy as shown by equation 4.7.

The magnitude of the nuclear charge $Ze$ as well as the numerical value of $b$ were determined from scattering experiments. It appears that Van den Broek[25] was the first to suggest that the positive nuclear charge might be equal to the atomic number $Z$ times the electronic charge $e$. Many investigations by Rutherford and co-workers led to a conclusion regarding the order of magnitude of nuclear radii. For gold, silver, and copper it appeared[26] that the distances of closest approach of

[24] H. Geiger and E. Marsden, *Phil. Mag.*, **25**, 604 (1913).

[25] A. van den Broek, *Phys. Zeits.*, **14**, 32 (1913).

[26] J. Chadwick, *Phil. Mag.*, **40**, 734 (1920).

fast alpha particles were less than 3.2, 2.0, and $1.2 \times 10^{-12}$ cm, respectively.

More recent evidence [27] indicates that the radii are considerably smaller than first expressed and that the radii of various nuclei should vary as the cube root of the number of constituent particles as given by the atomic weight. This would be expected if the volume required for each neutron and proton within the nucleus is about the same. A relationship for the heavy radioactive nuclei, expressing the disintegration constant or half-life in terms of the energy of the alpha particle and the effective radius of the nucleus, has been proposed.[28]

**4.9. Transmutation by Alpha Particles.** If the alpha particle should penetrate into the nucleus, then the coulomb law of repulsion would no longer completely regulate its behavior. New forces of an attractive nature would now appear. Scattering experiments indicated for the very heavy elements, a radius of the order of $.7 \times 10^{-12}$ cm. To bring an alpha particle to that position would from the coulomb repulsion require an energy $W$ of

$$W = \frac{2Ze^2}{r} = Z \times 0.411 \text{ Mev} \tag{4.9}$$

Thus for uranium whose $Z$ is 92, an energy oI 37.5 Mev would be expected. An alpha particle should thus be prevented from entering the nucleus by this exceedingly high barrier. On surmounting the barrier the particle would fall forward by virtue of the attractive forces. Such a distribution of the potential is shown in Figure 4.7. It should be equally hard for an alpha particle to leave the nucleus.

It was actually found possible to induce nuclear transmutation by the alpha rays from Radium C whose energy is only 5.5 Mev, similarly alpha particles emitted by many radioactive bodies have energies of only a few million electron volts.

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[27] E. Rutherford and J. Chadwick, *Phil. Mag.*, **50**, 889 (1925).

[28] G. Gamow and S. Rosenblum, *Comptes Rendus*, **197**, 1620 (1933).

This incompatibility was reconciled by the wave mechanical treatment of the process. Wave mechanics concedes [29] a finite probability for a particle with an energy less than that of the peak of the barrier being able to penetrate it. The greater the energy of the alpha particle and the lower the height of the barrier the greater is the probability of its passage. There is thus a close relationship between the energy of the emitted alpha particles and the half-life of the source.

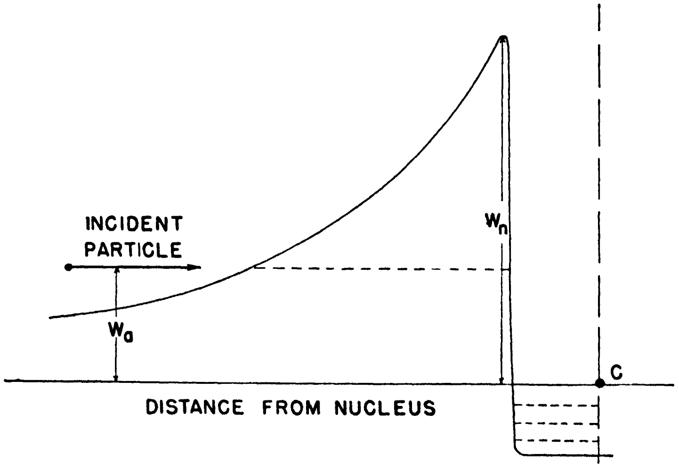

FIG. 4.7. The potential barrier of a nucleus.

As soon as devices for accelerating particles to high potentials were developed they were utilized to produce controlled alpha rays. Thus a cyclotron that will produce deuterons whose energy is 10 million electron volts is almost exactly in condition to produce alpha particles of 20 Mev. With sources of this kind most of the elements of the periodic table have been bombarded and the disintegration products observed. The addition of the energetic alpha particle to the nucleus makes an unstable or excited condition. The return to a stable nucleus may take place by any one of several competitive processes each with quite a different probability of occurrence. Thus the excited nucleus may emit a gamma ray, a neutron, a proton or, if sufficient energy is available, any combination of the particles. In most cases the yield of disintegrating atoms increases with the energy of the incident particle but this is by no means always true. One of the early reactions studied[30] was the bombardment of aluminum with alpha particles varying in energy up to 10.5 Mev. The range and number of the emitted protons were observed. The protons were found to have several definite ranges for any given energy of the exciting alpha particle, in all about eight groups being observed. As the energy of the alpha particles is increased the yield of protons shows distinct maxima at certain definite values of the energy. These particular alpha energies at which the number of protons was represented by peaks in the yield curve, were interpreted as being resonance channels through the nuclear barrier. For aluminum at least six such resonance energies were found, namely at 4.0, 4.49, 4.86, 5.25, 5.75, and 6.61 Mev. The width of some of the levels was also determined and found to be about 200 Kev.

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[29] G. Gamow, *Zeits. f. Phys.*, 51, 204 (1928); R. Gurney and E. Condon, *Nature*, 122 439 (1928).

This reaction could be represented as ${}_{13}\mathrm{Al}^{27}(\alpha, p){}_{14}\mathrm{Si}^{30}$, or it could be shown by the equation

$${}_{13}\mathrm{Al}^{27} + {}_{2}\mathrm{He}^{4} \rightarrow {}_{14}\mathrm{Si}^{30} + {}_{1}\mathrm{H}^{1} + Q$$

where $Q$ is the disintegration energy representing any inequality in the sums of the atomic masses on the two sides. From experiments of Chadwick and Constable,[31] $Q$ was found to be 2.07 Mev. Using the latest values of the masses given by Aston,[32] an unbalance of 0.00413 mass units is noted which would correspond to 3.83 Mev. It is quite probable that the more precise knowledge of the relative atomic masses can be deduced from the energies of the disintegration particles.

[30] W. E. Duncanson and H. Miller, *Proc. Roy. Soc.*, **146**, 366, 396 (1934).

[31] J. Chadwick and J. E. Constable, *Proc. Roy. Soc.*, **135**, 48 (1932).

[32] F. W. Aston, *Isotopes*, Arnold, London (1924), (1942).

Another very common transmutation effected by the alpha particle is one in which a neutron leaves the excited nucleus. The resulting nucleus thus has an atomic number greater by two than the original atom and heavier by three mass units. One of the most widely used reactions of this sort is a mixture of radon and beryllium used as a source of neutrons. The reaction can be abbreviated as ${}_4\mathrm{Be}^9(\alpha, n){}_6\mathrm{C}^{12}$ or it can be represented by the equation

$$ {}_4\mathrm{Be}^9 + {}_2\mathrm{He}^4 \rightarrow {}_6\mathrm{C}^{12} + {}_0n^1 + Q $$

The disintegration energy $Q$ is found to be necessary to account for a deficiency in mass on the right side of 0.006009 mass units, representing an energy of about 5.58 Mev. It has been found that a mixture of one millicurie of radon with sufficient beryllium[33] to absorb all the alpha radiation will emit about 6700 neutrons per second. Since the radon emits 37.1 million alpha particles in the same time, it would seem that at least one in every 5000 alpha particles is able to get into the beryllium nucleus and send out a neutron. This is a rather high probability for a nuclear reaction.

## QUESTIONS AND PROBLEMS

**1.** Alpha rays from thorium C′ (10.536 Mev) bombard nitrogen nuclei and protons are observed in the forward direction. Express their energy.

$$ {}_2\mathrm{He}^4 + {}_7\mathrm{N}^{14} \rightarrow {}_8\mathrm{O}^{17} + {}_1\mathrm{H}^1 $$

*Answer:* 8.69 Mev.

**2.** Alpha particles from radon have an energy of 5.486 Mev. By how much do the masses of radon and radium A differ?

*Answer:* 4.00973 mass units.

**3.** Lithium 7 is bombarded with protons whose energy is 1 Mev. Two alpha particles are produced each having the same energy. What is this energy and at what angles do the alpha particles emerge? If an alpha particle is observed leaving at right angles to the proton beam, what is its energy and the energy and direction of its companion alpha particle?

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[33] F. Paneth, E. Gluckauf, and H. Loleit, *Proc. Roy. Soc.*, **147**, 412 (1936).

*Answer:* 18.2 Mev, 85° 20′; 8.9 Mev, 9.2 Mev, 80° 30′.

**4.** In an alpha ray spectrograph, the radiation from polonium is to be bent into a circular path 30 cm in diameter. Express the uniform magnetic induction in gauss, that would be sufficient. What would be the energy difference for two beams registering on a photographic plate as lines 1 cm apart, for semicircular focusing?

*Answer:* 22,200 gauss, 0.36 Mev.

**5.** If the cross section for the disintegration of nitrogen by the alpha particles from thorium C′ is $10^{-25}$ cm$^2$, how many disintegrations are produced per second by one microcurie of thorium C′ surrounded by nitrogen gas under standard conditions?

*Answer:* approx. 2.

**6.** If $N$ alpha particles are scattered by a thin foil of silver to a certain receiver placed at an angle of 30° with the forward direction, how many scattered particles would be expected by the same receiver in the same time placed so as to allow a scattering angle of 60°? Also for 90°?

*Answer:* 0.072 $N$, 0.018 $N$.

**7.** Prove that an alpha particle will on elastically colliding with a proton, give up at most $\frac{16}{25}$ of its energy.

## CHAPTER 5

# BETA RAYS

**5.1. Historical.** That portion of the radiation from a radioactive source that was strongly deflected[1] by a perpendicular magnetic field was termed beta radiation. It was noted that the particles were negative in sign. They were soon identified as electrons emitted from the nuclei of the atoms of the source, some with a very high velocity. They were shown[2] to be in many ways very like the stream of cathode rays in a discharge tube. The energies of the beta particles however may be much greater than those of the usually observed cathode rays. Energies equivalent to those possessed by electrons falling through a potential of several million volts are not uncommon. For such electrons the relativity mass $m$ is the rest mass $m_0$ multiplied by the factor $(1 - \beta^2)^{-1/2}$ where $\beta$ is the ratio of the electron velocity $v$ to the velocity of light $c$, namely $3 \times 10^{10}$ cms per second. Velocities of these high energy particles may approach very closely that of light.

The electronic charge associated with the beta particles given off by a radioactive body may be observed by placing the emitter on the well-insulated plate of an electrometer and noting the positive charge acquired in a definite interval of time. The beta particles on leaving the nuclei of the emitting atoms, in effect, increase the nuclear positive charge. This is equivalent to increasing the atomic number of the element.

**5.2. Absorption and Range of Beta Particles.** Beta rays are generally far more penetrating than alpha particles. While the most energetic alpha particles may be completely absorbed in a few centimeters of air, beta particles may describe paths in air several hundred centimeters in length, or they may traverse layers of aluminum a few millimeters thick. On passing through successive layers of absorber the total number of beta particles in the beam as well as the energy of each particle decrease progressively.

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[1] H. Becquerel, *Comptes Rendus*, 130, 206 (1900).
[2] S. Mayer and E. von Schweidler, *Phys. Zeits.*, 1, 90 (1899).

Early investigation of beta spectra by magnetic spectrometers led to a false conclusion[3] regarding their nature. Particles were observed with energies varying continuously from zero up to some definite maximum value. Superimposed upon the continuous distribution were several groups of particles, each group having a definite discrete energy. These monoenergetic groups were later found to be electrons coming not from the nuclei but rather from the electronic orbits of the atoms. They arise from the internal conversion of gamma radiation that is emitted from the radioactive nuclei along with the beta radiation.

Even if the beta rays were originally all of the same energy, their ranges through matter would have a considerable spread in values. This follows from the fact that the electrons are so easily scattered by the atoms through which they pass.

The loss in energy of a beta particle on passing through matter is due to its production of ion pairs along its path. The number of ion pairs produced per centimeter of path increases as the velocity of the beta particle decreases. This varies from about 25 pairs per centimeter at 2 million electron volts to about 200 per centimeter at 40 KV. The ionization potential for oxygen and nitrogen is only about 14 volts. Actually the average energy loss per pair of primary ions formed is about 35 electron volts. This additional energy may result in secondary ionization so that the total number of ions per centimeter may be several times that of the number of primary ions. Some of the energy may be used for other purposes such as the excitation of molecules or atoms, that is, the lifting of electrons to unstable levels without actually removing them or producing ions.

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[3] O. von Baeyer, O. Hahn, and L. Meitner, *Phys. Zeits.*, 12, 273 (1911); 13, 264 (1912).

Each beta particle in its transit through a collection of atoms, in addition to losing energy to the electrons, may suffer a change in direction due more to its interaction with nuclei than with electrons. The average angle of deflection of the beta particles on traversing thin layers of material is found[4] to be proportional to the square root of the thickness $t$. For elements of various atomic number the scattering at a particular angle is found[5] to be proportional to the square of the atomic number $Z$.

At high energies the range of beta particles in matter varies almost linearly with the energy. At low energies the range is more nearly proportional to the square of the energy. This relationship is shown graphically in Figure 5.1, in which the range in aluminum is expressed in terms of the number of grams per cm$^2$ for complete absorption and the energy in million electron volts. In Table 5.1 a few values are given in successive horizontal columns for the energy of the beta particles in thousand electron volts, the ratio of the velocity of the electron to the velocity of light, the range in aluminum expressed in grams per cm$^2$, and the range in centimeters of air. The relationship between velocity and energy for electrons is shown graphically in Figure 5.2, for energies up to 4 Mev. A more extensive range is presented in Table A III.

TABLE 5.1

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Energy (Kev). . | 2 55 | 10.5 | 24.7 | 46 6 | 79 1 | 127 8 | 204.7 | 341 | 662 | 1127 | 2058 | 3114 |
| $\beta = v/c$ . | 0 1 | 0 2 | 0 3 | 0 4 | 0 5 | 0 6 | 0 7 | 0 8 | 0 9 | 0.95 | 0 98 | 0 99 |
| Grams/cm$^2$ | 0.00005 | 0.00027 | 0.0012 | 0 0041 | 0 0087 | 0 0215 | 0 045 | 0 100 | 0 260 | 0 525 | 1 03 | 1 57 |
| $R$ (cm)... | 0 04 | 0 23 | 1 0 | 3 4 | 7 3 | 17 9 | 37 5 | 83 | 217 | 437 | 860 | 1300 |

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[4] J. A. Crowther, *Proc. Roy. Soc. A*, **84**, 226 (1910).

[5] J. A. Crowther and B. F. Schonland, *Proc. Roy. Soc. A*, **100**, 526 (1922).

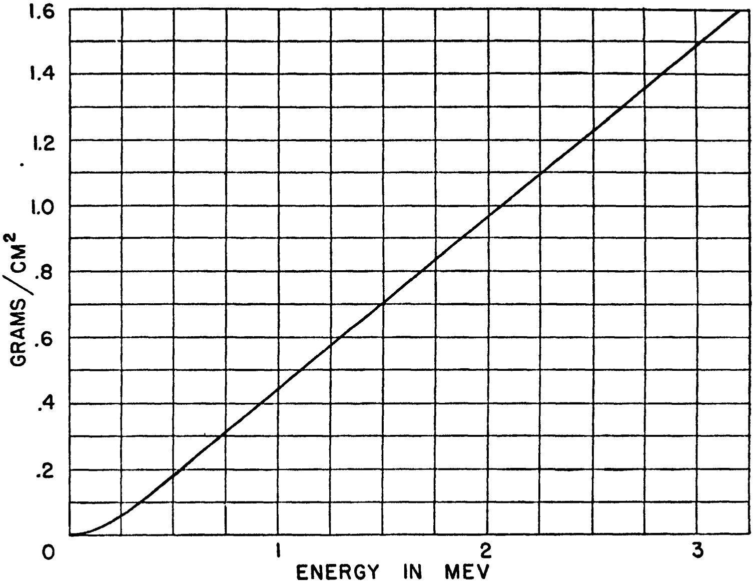

FIG. 5.1. Range in aluminum for complete absorption.

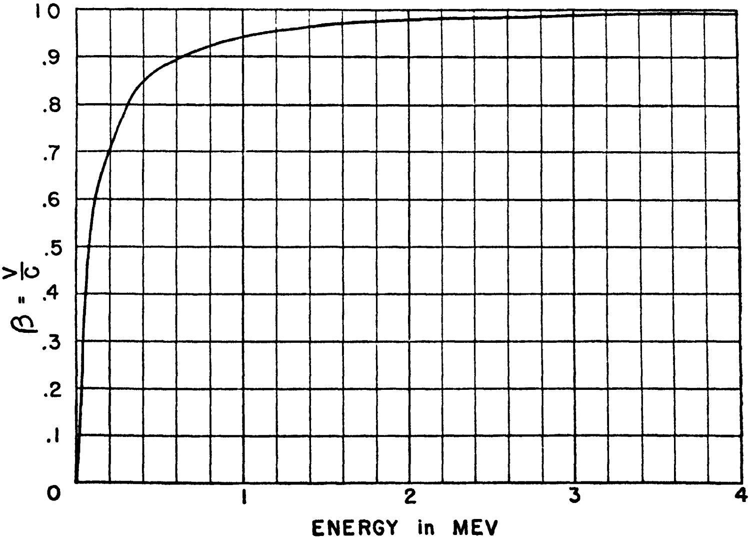

Fig. 5.2. Relationship between energy and velocity relative to that of light for electrons.

**5.3. The Feather Rule for Beta Energies.** Feather observed that the maximum range of beta particles in aluminum could be used empirically to evaluate the energy of the particles.[6] Experimentally, the intensity of the radiation is noted as the thickness of an interposed aluminum absorber is progressively increased. These data may then be represented as in Figure 5.3, where the ordinate is the intensity plotted on a logarithmic scale. It is noted that for the radiation under consideration thicknesses of aluminum greater than 0.36 grams per cm$^2$ produce almost no diminution in intensity. At this point only

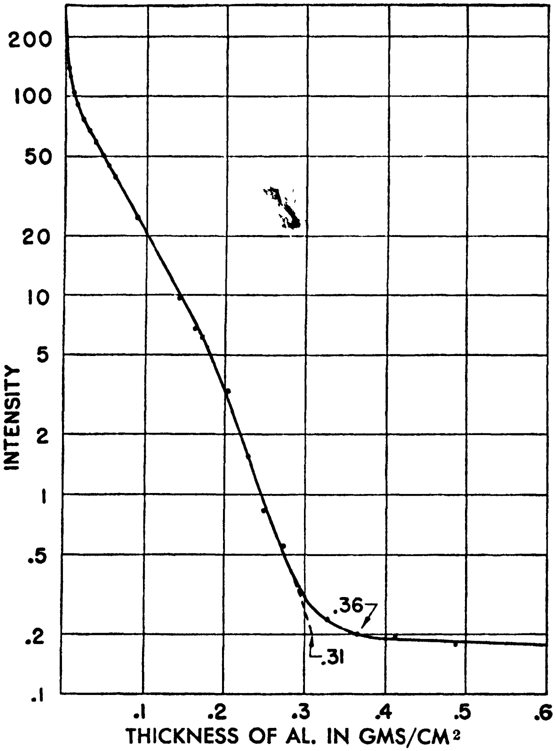

Fig. 5.3. The intensity of beta rays from indium 116 on passage through aluminum.

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[6] N. Feather, *Proc. Camb. Phil. Soc.*, **34**, 599 (1938).

gamma radiation is transmitted. It is thus possible to determine with a fair degree of accuracy the amount of absorber needed to just completely absorb the beta radiation. The relationship deduced by Feather is

$$R\left(\frac{\text{gms}}{\text{cm}^2}\right) = .543E\ (\text{Mev}) - 0.16 \qquad \textbf{(5.1)}$$

or

$$E\ (\text{Mev}) = \frac{R}{.543} + 0.294 \qquad \textbf{(5.2)}$$

For the data shown, which represent the beta radiation from the indium isotope of mass 116, complete absorption seems to be produced by about 0.36 grams per cm$^2$. This value, when inserted in equation 5.2, indicates an energy of 0.960 Mev. It is interesting to note that for this same energy the magnetic beta spectrometer as shown in Figure 2.12 indicates a value of 0.86 Mev. Thus in noting the maximum range, attention must be given to the resolution of the observed curve. In the figure shown, it is reasonable by analysis to choose a range of 0.31 gms. per cm$^2$. This results in a value of energy in complete agreement with the magnetic spectrometer.

**5.4. The Beta Spectrum.** The distribution of energy characteristic of the particles comprising the beta radiation from a radioactive source may be studied by a Wilson cloud chamber. The expansion chamber is provided with a thin window for the particles to enter, and a strong perpendicular magnetic field to produce a curvature in their paths. Such beta ray tracks are shown in Figure 5.4. A measurement of the radius $\rho$ of each circular trace together with the known magnetic induction $B$ allows an evaluation of the energies of the individual beta particles. By counting a sufficiently large number of tracks, the fluctuations are averaged and a histogram as shown in Figure 5.5 is obtained. The ordinates represent the number of observed particles in successive equal intervals of $B\rho$. A smooth curve may be drawn so as to average any irregularities. The

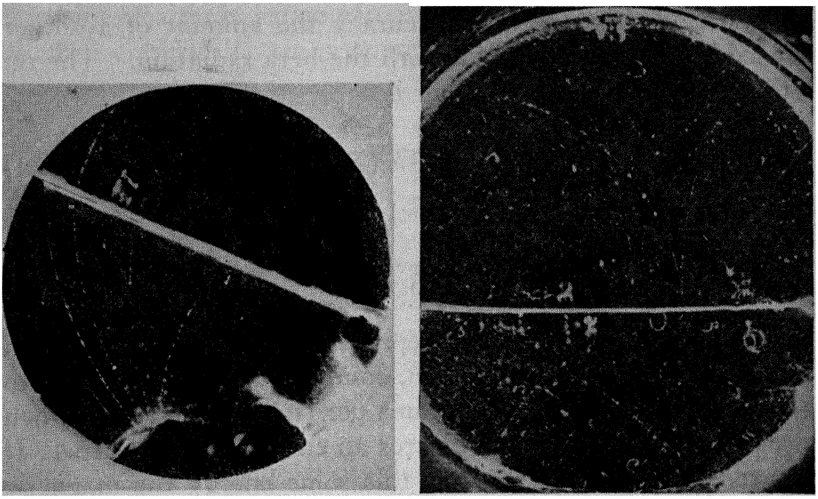


Fig. 5.4. Cloud chamber tracks of electrons moving in a magnetic field directed into the page.

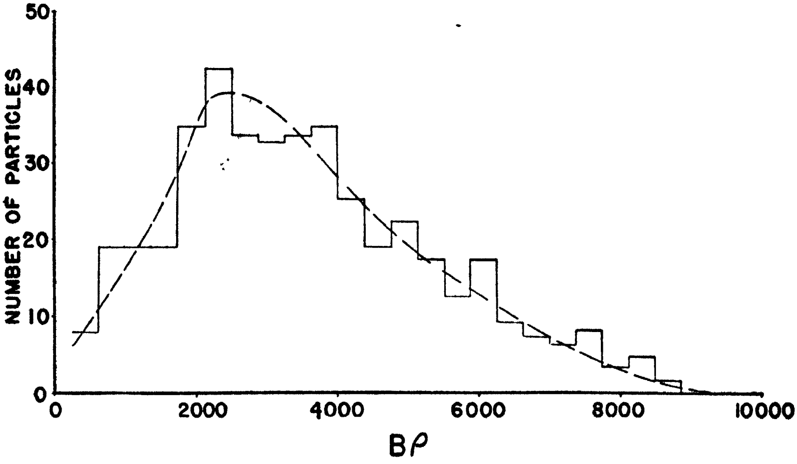
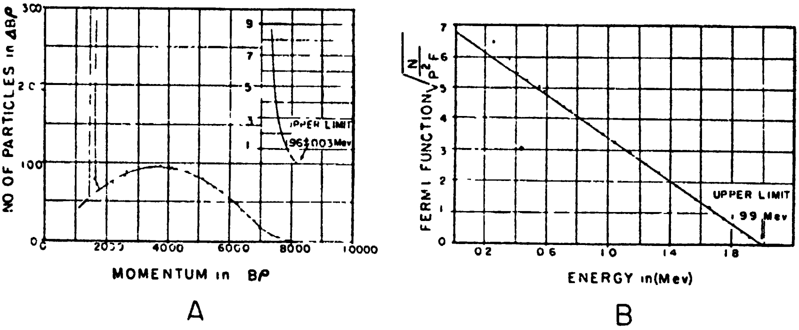


Fig. 5.5. Distribution of momentum among a large number of beta particles.

general form of such contours is that of a probability curve extending from a low value at zero momentum up through a most probable range to a definite limiting maximum value of the energy.

The observed distribution is quite likely to be an incorrect representation of the true number of particles at each energy. Because of their loss in energy and scattering in the gas there will appear to be relatively too many particles of low energy. By using hydrogen gas in the chamber this error can be greatly reduced.



A B

Fig. 5.6. The beta spectrum of indium 114 and its behavior according to the Fermi theory.

More exact distribution curves may be obtained by the use of beta ray spectrometers. These are of various types (as previously described), and in them the beta particles may go from the source to the receiver with little or no scattering agent intervening. The type of distribution curve and the high precision attainable at the maximum energy cutoff is illustrated in Figure 5.6*A*. These data were obtained with a semicircular magnetic focusing spectrometer, using as a source the isotope of indium of mass 114.[7]

**5.5. The Neutrino.** If it be assumed that only discrete energy states can characterize the nucleus, then this observed continuous distribution of beta energies is difficult to explain. Two possibilities might allow a continuous distribution. One of these involves the abandonment of the notion of the conservation of energy in processes occurring within the nucleus. This suggestion was proposed,[8] perhaps not seriously, by Bohr, Kramers, and Slater.

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[7] J. L. Lawson and J. M. Cork, *Phys. Rev.*, 57, 982 (1940).

Another possibility would be that in the transition from one definite energy state to another only a portion of the fixed energy difference is carried off by the beta particle. The remaining part of the energy is carried away by some other non-detectable type of radiation. To satisfy this need a new elementary particle was postulated. This particle was called the "neutrino" and is visualized as being a neutral particle whose mass is perhaps less than that of the electron. Because of the absence of charge it can pass through matter with little or no absorption and cannot be detected directly.

A rather crucial calorimetric experiment justifying this conclusion was carried out by Ellis and Wooster.[9] Radium E emits electrons with a maximum energy of 1050 Kev and with an average energy of about 390 Kev. In the thermal measurement of the energy released, an average value of 350 Kev was observed. It was accordingly concluded that the remainder of the energy was not released in any form ultimately converted into heat within the heavily shielded calorimeter and hence must have been carried off as an undetectable radiation. More direct experiments to establish with certainty the existence of the neutrino have been carried out by Crane and Halpern, and by Allen, and have been described on page 17. In general they are not completely conclusive.

**5.6. The Positron.** In 1932, in cosmic ray studies, C. D. Anderson[10] observed, in a vertical Wilson chamber, tracks with a curvature indicating that the particles carried a positive charge. Although they were at first announced as protons, subsequent studies showed these particles to be both as to mass and as to size identical with electrons except opposite in sign. They were called "positrons."

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[8] N. Bohr, H. A. Kramers, and J. C. Slater, *Zeits. Phys.*, 24, 69 (1924).

[9] C. D. Ellis and W. A. Wooster, *Proc. Roy. Soc. A*, 117, 109 (1927).

[10] C. D. Anderson, *Phys. Rev.*, 41, 405 (1932); 43, 491 (1933).

It was almost immediately found that many of the induced radioactivities, on decaying to normal atoms, emitted positrons. This is particularly true of those radioactive isotopes that are less in mass than the stable isotopes of the same element such as $O^{15}$, $N^{13}$, $C^{11}$, etc.

The form of the distribution curve for the positrons is very much like that observed for negative particles. Certain isotopes such as $Cu^{64}$ emit simultaneously both negative and positive particles with a single half-life. The upper limit of the spectrum for the $Cu^{64}$ positrons is 0.66 Mev compared with 0.58 Mev for the negatives. The difference may be due to the action of the positive nucleus on the departing particles, being an attraction for the negatron and a repulsion for the positron.

The stopping power of matter for positrons has been found to be quite similar to that displayed for negative electrons.[11]

**5.7. The Specific Charge of the Electron and the Positron.** The ratio of the charge $e$ to the mass $m_0$ for beta particles from radium was first determined by Becquerel in 1900, establishing the fact that these particles were the same as cathode rays or electrons.[12] He obtained a value $1 \times 10^7$ electromagnetic units per gram. One year later, W. Kaufmann[13] in a more accurate determination found in the same units a value of $1.77 \times 10^7$. Since that time, a great number of investigations dealing with this quantity have been carried out. The careful investigation by Bucherer[14] was considered to yield the best value until recently, namely $1.763 \times 10^7$ EMU per gm. The value of $e/m$ as observed, of course, gets smaller as the velocity of the beta particle increases, since the mass also increases. The magnitude of this change in mass is shown in Table A III, column 4.

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[11] B. R. Curtis, *Phys. Rev.*, **53**, 986 (1938).
[12] H. Becquerel, *Comptes Rendus*, **130**, 809 (1900).
[13] W. Kaufmann, *Phys. Zeits.*, **2**, 602 (1901).
[14] A. H. Bucherer, *Ann. d. Phys.*, **37.3**, 592 (1912).

With the discovery of the positron, it became of interest to see if its specific charge was exactly that of the negative electron. This subject could be advantageously studied by using as a source radioactive copper of mass 64, since it emits both positives and negatives simultaneously. It was shown[15] that $e/m_0$ is the same for both types of particles, within an accuracy of better than 2%.

The value of the specific electronic charge as edited by Birge[16] is $(1.7592 \pm 0.005) \times 10^7$ EMU per gm.

**5.8. The Fermi Theory of Beta Decay.** In 1934, Fermi proposed a theory of beta decay.[17] He assumed that the negative beta particle was emitted by a transition within the nucleus in which a neutron was converted into a proton. Along with the electron, a neutrino escaped from the nucleus. The total energy of the pair from a definite emitter is a constant. A study of the energy distribution of the beta particles reveals the manner in which the energy is shared between the neutrino and the electron. To explain the observed distribution it became necessary to make an assumption regarding the interaction between the electron-neutrino field and that of the heavy particle.

The form of the derived expression for the probability $P$ of the ejection, in unit time, of a beta particle whose energy lies between $W$ and $W + dW$, expressed in units of $mc^2$, was given as

$$P\,dW = KF(Z, W)pW(W_m - W)^2\,dW \qquad (5.3)$$

where $p$ is the momentum of the electron in units of $mc$ and is equal to $(W^2 - 1)^{1/2}$. Fermi showed that the function $F(Z, W)$ could be explicitly evaluated. Kurie[18] rearranged the equation so that it could be readily subjected to test by the observed data. In this form the number of particles in each successive, equal interval of momentum was denoted as $N$ and the reduced equation became

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[15] C. T. Zahn and A. H. Spees, *Phys. Rev.*, **53**, 357 (1938); A. H. Spees and C. Zahn, *Phys. Rev.* **58**, 861 (1940).

[16] R. T. Birge, *Rev. Mod. Phys.*, **13**, 233 (1941).

[17] E. Fermi, *Zeits. f. Phys.*, **88**, 161 (1934).

[18] F. Kurie, J. Richardson, and H. Paxton, *Phys. Rev.*, **49**, 368 (1936).

$$\left(\frac{N}{F}\right)^{1/2} = A - B(W + 1) \tag{5.4}$$

in which $A$ and $B$ are constants.

Thus on plotting the square root of $\frac{N}{F}$ against $(W + 1)$, a straight line of negative slope should be obtained. The intercept on the energy axis would be one $mc^2$ greater than the maximum beta transition energy $W_m$.

Early data were obtained by the counting of tracks within a cloud chamber. With air in the chamber a large percentage of the low energy tracks were multiply-scattered. More reliable observations were made by using hydrogen in the chamber. On making plots according to the Kurie arrangement of the Fermi equation, a partial test could be made either of the theory or of the data used. If the theory is correct, then good data should give a straight line. Any deviation from a straight line might then be interpreted as an insufficiency in the theory or in the observed results. All early data treated in this way failed to yield linear plots with the Fermi equation.

**5.9. The Konopinski-Uhlenbeck Theory.** The observed apparent failure of the Fermi theory stimulated further theoretical consideration of beta decay. Following the same procedure as Fermi, but by introducing and including higher-order derivatives of the interaction between the heavy particle and the electron-neutrino field, Konopinski and Uhlenbeck[19] were led to several alternative expressions for the beta distribution. Certain of these expressions could be excluded at once, from energy considerations. The expression offering most promise was, when rearranged to yield a Kurie plot, quite similar to that for the Fermi equation. The only difference was, that instead of the term $\left(\frac{N}{F}\right)^{1/2}$, there appeared the term $\left(\frac{N}{F}\right)^{1/4}$.

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[19] E. J. Konopinski and G. E. Uhlenbeck, *Phys. Rev.*, 48, 107 (1935).

The best data were put in proper form to test this relationship and in most cases a straight-line plot resulted. It was thus at first assumed that the Konopinski-Uhlenbeck theory was correct. As the technique of taking data improved it became apparent that the experimental data were not reliable.

At low energies, serious errors due to back scattering and multiple scattering existed. The beta spectra of several emitters have been resurveyed, taking great care to reduce back scattering and multiple scattering. It is now apparent that when these data are checked by the Kurie plot, the Fermi equation is more nearly satisfied than the Konopinski-Uhlenbeck relationship. This is shown quite clearly in Figure 5.7, which represents [20] the positron spectrum from a radioactive copper isotope of mass 64 having a half-life of 12.8 hours. Two sets of data were taken. In one experiment the thick source consisted of a mass of copper of 50 mgms. per cm$^2$ while in a

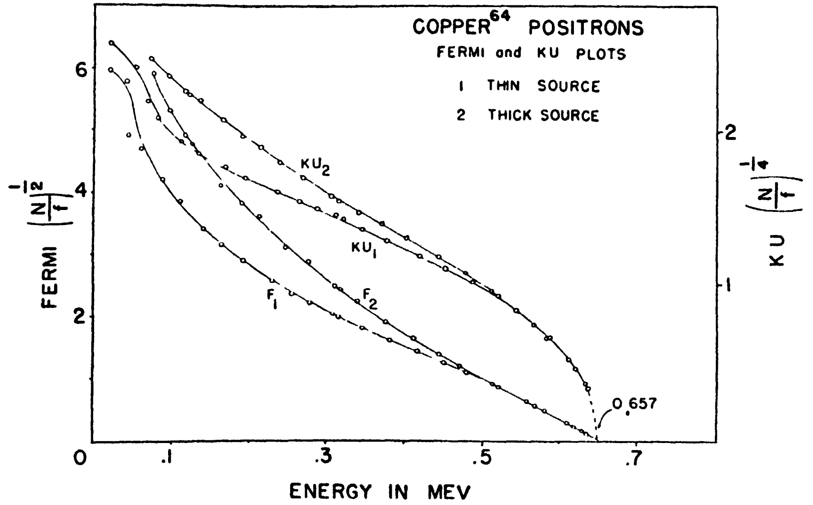

Fig. 5.7. The beta spectrum of copper 64, using a very thin source and a thick source.

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[20] A. W. Tyler, *Phys. Rev.*, **46**, 127 (1939).

second run having an equally strong radioactivity, the mass of the copper was only 2 mgms. per cm$^2$. Each observed distribution was plotted both according to the Fermi equation and the K-U equation. It is apparent that except for low energies the Fermi curve seems most linear. This same result is more strikingly observed in the beta spectrum of the indium isotope of mass 114 reported[21] by Lawson and Cork. This electron distribution as observed in a magnetic spectrometer is shown in Figure 5.6*A*. The enlarged plot in the upper right corner shows in more detail the upper limit of energy at 1.96 Mev. On the Kurie plot, following the Fermi equation, shown in Figure 5.6*B*, the points lie very closely along a straight line whose intercept on the energy axis is at 1.99 Mev.

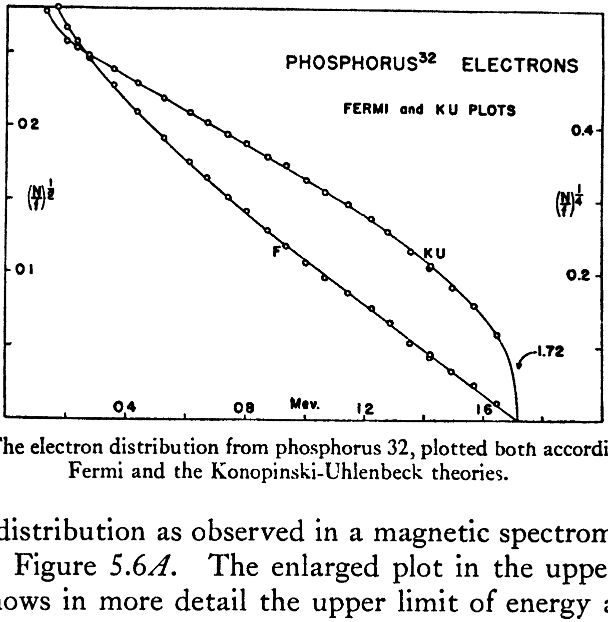

Fig. 5.8. The electron distribution from phosphorus 32, plotted both according to the Fermi and the Konopinski-Uhlenbeck theories.

The spectrum of the beta radiation from phosphorus 32 has been widely studied. The distribution of momentum, as observed by Lawson,[22] is plotted in Figure 5.8 both according to the Fermi theory and the Konopinski-Uhlenbeck modification. The fit with the Fermi theory seems definitely better.

[21] J. L. Lawson and J. M. Cork, *Phys. Rev.*, 56, 127 (1939).
[22] J. L. Lawson, *Phys. Rev.*, 55, 1136 (1939).

**5.10. Nuclear Spin and Magnetic Moment.** One of the fundamental postulates of the Bohr[23] theory of atomic structure was to assume the quantization of the momentum of the electron in its orbit about the nucleus. The angular momentum of the atom was expressed as integral multiples of $h/2\pi$ where $h$ is the well-known Planck constant. In 1925, Uhlenbeck and Goudsmit[24] proposed that the electron itself has an axis of symmetry about which rotation takes place. This spinning electric charge would be equivalent to an electric current in a circular conductor and would result in a magnetic dipole of definite moment. In this way they could account for the four quantum numbers found empirically necessary in the classification of atomic energy levels. It was necessary that the spin of the electron be considered to be one-half, in the above-mentioned units. Similarly, the proton and neutron are both believed to have spins of one-half.

It must therefore be expected that any nucleus made up of these elementary particles should have a resultant magnetic moment. Evidence for the existence of the nuclear magnetic moment for hydrogen was first offered by O. Stern[25] and his co-workers. A beam of hydrogen molecules was projected perpendicularly through a strong magnetic field having a steep gradient at right angles to the beam. As a result, the beam is separated into a number of components interpretable as due to the magnetic sub-states, from which the magnetic moment is evaluated.

An improved method for measuring magnetic moments using an atomic beam has been developed by Rabi and his associates.[26] In this method it also is possible to say whether the magnetic moment is positive or negative. The expression for the magnetic moment of the electron, $\mu_e$ is

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[23] N. Bohr, *Phil. Mag.*, **26**, 1, 476, 857 (1913).

[24] G. E. Uhlenbeck and S. Goudsmit, *Naturwiss*, **13**, 953 (1925); *Nature*, **117**, 264 (1926).

[25] I. Estermann and O. Stern, *Zeits. f. Phys.*, **85**, 17 (1933); O. Frisch and O. Stern, *Zeits. f. Phys.*, **85**, 4 (1933).

[26] I. Rabi, J. M. Kellogg, and J. Zacharias, *Phys. Rev.*, **46**, 157, 163 (1934); **49**, 421 (1936); **56**, 738 (1939).

$$\mu_e = \frac{e}{2mc}\frac{h}{2\pi} \tag{5.5}$$

This magnetic moment is usually referred to as a "Bohr magneton." For a proton, the mass is larger by the factor 1833, so the magnetic moment might be expected to be smaller by the same factor. This quantity may be designated $\mu_o$, and is called a "nuclear" magneton. It has the value $5.02 \times 10^{-24}$ gauss cm$^3$. The value of the magnetic moment $\mu$ actually observed for the proton is found to be $+2.7896\mu_o$. This larger value has been theoretically explained. The magnetic moment of the deuteron has been found to be +0.855 nuclear magnetons. It thus follows that for the neutron the magnetic moment is −1.934 nuclear magnetons; that is, the neutron behaves as if a predominantly negative charge is spinning. More recently an interesting method of determining nuclear magnetic moments utilizing radio techniques has been proposed.[27]

The resultant angular momentum of a nucleus can be determined [28] from an analysis of the hyperfine structure characteristic of its spectrum. The spins of nuclei of odd atomic weight are in general odd multiples of $\frac{1}{2}h/2\pi$, while isotopes of even atomic weight have either zero spin or small integral multiples of $h/2\pi$. The resultant spin is the vector sum of the orbital angular momenta and the spins of the individual nuclear particles. The orbital angular momenta are integer multiples of $h/2\pi$. The appearance of half-integer values for the spin of the resultant atom was thus considered as evidence that the spins of the individual nuclear particles, that is, both neutrons and protons, are each one-half $h/2\pi$. The spin of the neutrino and the meson may also each be one-half, although this cannot be assumed with certainty.

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[27] F. Bloch, W. Hansen, and M. Packard, *Phys. Rev.*, 69, 127 (1946).
[28] E. Wick, *Acad. Lencei Atti*, 21, 170 (1935).

**5.11. The Sargent Rule.** It was observed by Sargent[29] in 1933 that for many of the naturally radioactive elements a simple relationship existed between the maximum energy of the beta radiation and the decay constant or half-life $T_{1/2}$ of the activity. On plotting the logarithm of the disintegration constant λ versus the logarithm of the maximum beta energy, a straight line of slope 5 was found. Thus an equation of the form

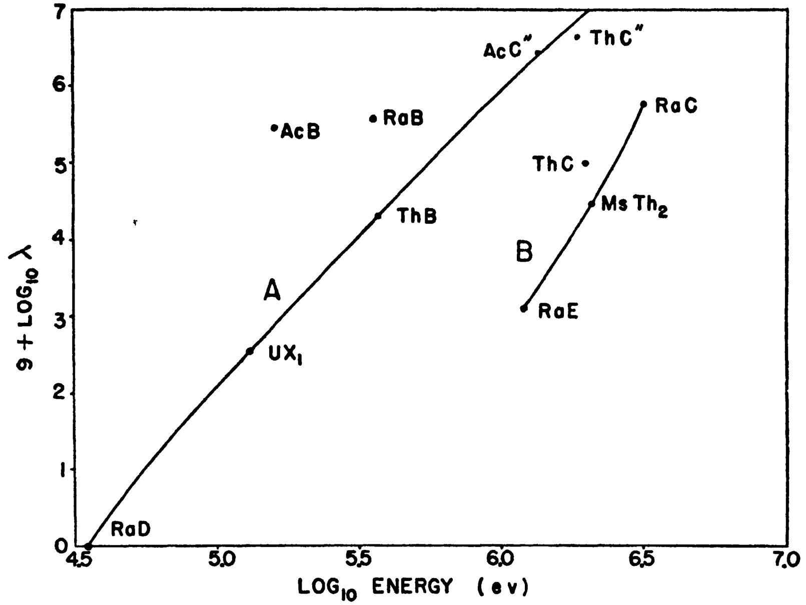

FIG. 5.9. The Sargent relationship for a few of the natural beta emitters.

$$T_{1/2}W^5 = c \tag{5.6}$$

seemed valid for the relationship where $c$ is a constant. Several activities seemed to lie off the line in the graph and in fact another group could be formed represented by another equation with a constant $c'$ different from $c$ by a large factor. This is shown in Figure 5.9.

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[29] B. W. Sargent, *Proc. Roy. Soc.*, 139, 659 (1933).

Of the many induced radioactivities now known to exist, several such groups may be formed. Those emitters for which the constant $c$ is a minimum are said to undergo "allowed" transitions. The next group of emitters for which $c$ is about 100 times as large, decay by "first forbidden" transitions, the following group with correspondingly larger $c$ by "second forbidden" transitions, and so on.

In optical spectra it was found desirable to formulate a set of selection rules under which the possibility of a certain transition could be determined. In a similar way criteria can be established so that the probability of a particular nuclear disintegration can be predicted.

On the emission of a particle the nucleus changes from an initial to a final state and the change in spin indicates the probability or half-life of such a transition. At the same time a change may or may not occur in another attribute of the system of particles called "parity." This quantity is either even or odd for a nucleus, depending upon its symmetry characteristics. It may be regarded empirically as an additional quantum number describing the energy level.

Those beta spectra falling on the first Sargent curve—that is, a small value of $c$—are termed "allowed" spectra. For them the change in spin number is small and it was for this type of transition that the theories were developed. Unfortunately these "allowed" spectra have either a very short half-life or a very low energy and are thus not susceptible to precise measurement. The spectra that have received the most experimental attention such as that from Ra E(Bi 210) whose half-life is 5.0 days with a maximum energy 1.17 Mev and from phosphorus 32, whose half-life is 14.3 days and maximum energy 1.71 Mev, are forbidden spectra. Hence an exact agreement with theory should not be expected.[30]

In certain special cases this difficulty does not exist. In the indium isotope of mass 114, beta emission is triggered by and

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[30] E. J. Konopinski and G. E. Uhlenbeck, *Phys. Rev.*, 10, 308 (1941).

TABLE 5.2. BETA SPECTRA-KONOPINSKI FUNCTION

| *Emitter* | $T_{1/2}(Sec)$ | $W(mc^2)$ | $FT_{1/2}$ |
|---|---|---|---|
| C 11 | 1230 | 2.86 | $3.46 \times 10^3$ |
| F 17 | 64 | 4.78 | 3.35 |
| O 15 | 125 | 4.37 | 4.16 |
| Mg 23 | 11.6 | 6.52 | 3.09 |
| P 29 | 4.6 | 8.16 | 3.80 |
| S 31 | 3.2 | 8.57 | 3.26 |
| A 35 | 1.9 | 9.57 | 3.45 |
| Sc 41 | .9 | 10.68 | 2.48 |
| Y 88 | 7200 | 2.34 | 5.00 |
| In 114 | 72 | 3.96 | 3.50 |
| Mg 27 | 612 | 4.52 | $4.0 \times 10^4$ |
| P 30 | 153 | 6.87 | 5.0 |
| K 38 | 462 | 5.50 | 4.0 |
| Ti 45 | $1.1 \times 10^4$ | 3.35 | 5.5 |
| Y 47 | 1980 | 4.72 | 6.9 |
| Co 60 | 640 | 3.94 | 3.6 |
| In 110 | 3900 | 3.2 | 4.0 |
| Ag 106 | 1470 | 5.0 | 4.6 |
| RaB 214 | 1608 | 1.30 | 4.0 |
| Li 8 | .88 | 24.5 | $2.8 \times 10^5$ |
| Cl 34 | 1980 | 5.9 | 2.8 |
| Sc 48 | $1.6 \times 10^5$ | 2.26 | 2.8 |
| Tl 204 | 253 | 4.1 | 2.0 |
| AcC′ 207 | 291 | 3.73 | 1.3 |
| ThC′ | 186 | 4.51 | 2.8 |
| ThB 212 | $3.8 \times 10^4$ | 1.7 | 1.5 |
| $UX_2$ 234 | 68 | 5.5 | 2.7 |
| Ca 49 | 9000 | 5.5 | $2.1 \times 10^6$ |
| Fe 59 | $8 \times 10^6$ | 1.9 | 4.2 |
| Rb 89 | 900 | 8.5 | 3.8 |
| Pd 107 | $4.7 \times 10^4$ | 3.0 | 1.2 |
| Sb 122 | $2.5 \times 10^5$ | 2.6 | 3.2 |
| Os 193 | $3.9 \times 10^6$ | 1.69 | 3.9 |
| An 196 | $4.0 \times 10^5$ | 1.7 | 2.0 |
| Pl 239 | $2.0 \times 10^5$ | 1.9 | 4.0 |
| Na 22 | $1 \times 10^8$ | 2.08 | $2.0 \times 10^7$ |
| P 32 | $1.2 \times 10^6$ | 4.37 | 8.6 |
| Cl 38 | 3330 | 10.38 | 2.1 |
| Mo 99 | $2.4 \times 10^5$ | 3.9 | 4.0 |
| W 185 | $6.7 \times 10^6$ | 1.9 | 4.0 |
| ThC 212 | 3630 | 5.4 | 1.3 |
| RaC 214 | 1180 | 7.1 | 1.7 |
| MsTh I 228 | $2.1 \times 10^8$ | 1.1 | 1.0 |
| MsTh II 228 | $2.2 \times 10^4$ | 4.1 | 2.5 |
| Ra E 210 | $4.3 \times 10^5$ | 3.3 | 9.8 |

follows the radiation of a long-lived gamma ray. The half-life of the gamma radiation is 50 days which is followed by a beta emission of half-life only 72 seconds and energy 1.98 Mev. This is thus an "allowed" beta ray of high energy yet because of its origin it is observable as if it had a very long half-life.

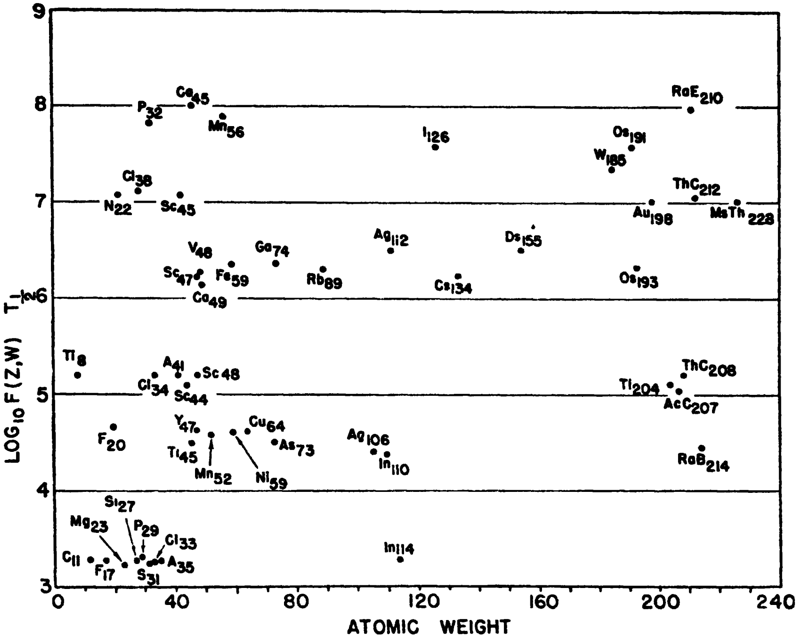

Fig. 5.10. Konopinski function to show the degree of "forbiddenness" of beta spectra.

The spectrum of this radiation is shown in Figure 5.6*A* and the Kurie plot based upon the Fermi equation in Figure 5.6*B*. It is apparent that except for the lowest energies where measurements are less exact, the agreement is excellent.

To show the degree of "forbiddenness" of a beta ray, Konopinski has developed [31] a function $F(Z, W_m)$ which, while much more complicated, is like the Sargent term in that when multiplied by the half-life $T_{1/2}$ it gives a constant for any similar group of beta emitters. In Table 5.2 are listed several representative beta emitters, among the great many known to exist. Column 2 shows their half-lives in seconds and in column 4 are the products of the Konopinski functions $F$ and the half-lives $T_{1/2}$. These data are shown graphically in Figure 5.10, being spread out along the abscissa according to atomic weight. It is apparent that regardless of atomic weight several fairly well-defined groups appear as shown by the horizontal lines, each representing a different order of "forbiddenness" for the transition.

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[31] E. J. Konopinski, *Rev. Mod. Phys.*, **15**, 209 (1943).

**5.12. "K" Electron Capture.** From theoretical considerations, it was suggested by Yukawa [32] that any long-lived positron-emitting nucleus might also decay by capturing one of its own orbital "K" electrons. The branching ratio for the two modes of disintegration was shown [33] to depend upon the energy available, the density of electrons and the spin change associated with the positron emission. The probability of capture should increase with the half-life or with the magnitude of the spin change associated with the transition.

A successful search for this phenomenon was made by Alvarez in 1938.[34] On bombarding titanium with deuterons a radioactivity was produced which was identified as due to an isotope of vanadium of mass 49. The half-life was 600 days. The only possibility of recognizing the reaction was to study the X-rays emitted by the atom. If a vanadium ($Z = 23$) nucleus captures a K electron, the nucleus becomes titanium ($Z = 22$) and the X-rays emitted as the "K" shell is refilled will be the characteristic X-rays of titanium. These were positively identified by their characteristic absorption. Many other cases of "K" electron capture have now been discovered.

**5.13. Transmutation by Electrons.** Several early attempts [35] to induce radioactivity in elements by bombardment with electrons having energies up to a million electron volts were unsuccessful. On considering the problem theoretically Guth[36] concluded that success might be expected if the energy of the incident electrons exceeded in value the threshold for photoelectric disintegration. Since beryllium had been shown[37] to have a photoelectric threshold of 1.6 Mev it became possible to test the theory with the 1.8 Mev output of the Van de Graaf generator at Notre Dame University. The reaction anticipated[38] would be representable by the symbol ${}_4\mathrm{Be}^9(e,\ n){}_3\mathrm{Li}^8$ or by the equation

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[32] H. Yukawa and S. Sakata, *Proc. Phys. Math. Soc. Japan*, **18**, 128 (1936).

[33] G. Uhlenbeck and H. Kuiper, *Physica*, **4**, 601 (1937); C. Moller, *Phys. Rev.*, **51**, 84 (1937).

[34] L. Alvarez, *Phys. Rev.*, **53**, 213 (1938); **54**, 486 (1938).

[35] J. Livingood and A. Snell, *Phys. Rev.*, **48**, 851 (1935); G. P. Thomson and J. Saxton, *Phil. Mag.*, **23**, 241 (1937).

$$ {}_4\mathrm{Be}^9 + {}_{-1}e^0 \rightarrow {}_3\mathrm{Li}^8 + {}_0n' \rightarrow {}_4\mathrm{Be}^8 + {}_0n' + {}_{-1}e^0 \quad \mathbf{(5.7)} $$

In carrying out the experiment, neutron emission was detected by noting the activation induced in foils of silver, rhodium, or indium placed near the target. For incident energies greater than 1.63 Mev, positive evidence of neutron production was observed. It was further shown by using different thicknesses of beryllium that the disintegration was not due to gamma or X-rays arising from the decelerated electrons. The cross section at 1.73 Mev for the reaction was found to be only of the order of $10^{-31}$ cm$^2$. Lithium 8 has a half-life of 0.88 sec. and there is some question regarding the stability of beryllium 8 so that no delayed radioactivity was observed.

Since this first successful disintegration experiment it has been found possible to excite many radioactivities in heavy elements by electrons. The activities which can be produced in this manner are those associated with the excited state of a normally stable atom. Such metastable states, representing energy levels up to 1.5 Mev or more, exist in indium, lead, strontium, and silver and perhaps many other elements.

[36] E. Guth, *Phys. Rev.*, 55, 412 (1939).

[37] J. Chadwick and M. Goldhaber, *Proc. Roy. Soc.*, 151, 479 (1935).

[38] G. B. Collins, B. Waldman, and W. Guth, *Phys. Rev.*, 56, 876 (1939).

## QUESTIONS AND PROBLEMS

**1.** Show that the radius of curvature $\rho$, of an electron whose energy is $W$ Mev, moving at right angles to a field of $B$ gauss is

$$\rho = \frac{10^4}{3B}\sqrt{W(W + 1.02)} \text{ cms}$$

**2.** What thicknesses of aluminum will effectively absorb the beta rays from (*a*) phosphorus 32, and (*b*) lithium 8, making use of the Feather rule?

*Answer:* 0.28 cm, 2.3 cm.

**3.** In a cloud chamber, a high energy electron describes a track of radius 30 cm in a magnetic field of 9000 gauss. Express its momentum in gauss cm and its energy in Mev.

*Answer:* 270,000 gauss cm, 80.5 Mev.

**4.** A beta spectrometer as shown in Figure 2.14 with a solenoidal winding of 10 turns per cm, carrying a current of 20 amps., brings particles back to the axis 60 cms from their source on the axis. The circular slit through the baffle at the center has a diameter of 20 cm. Express the momentum in gauss-cm and the energy of the particles focused at this current. On changing the current to 10 amperes or to 40 amperes, show what happens.

*Answer:* 2723 gauss-cm, 0.45 Mev.

**5.** An electron of energy 1 Mev is elastically scattered through an angle of 120° by a carbon nucleus at rest at the surface (see Figure 5.4*A*). What energy and what momentum transfers take place?

*Answer:* Carbon nucleus recoils at approximately 30° with 269 ev.

## CHAPTER 6

# GAMMA RADIATION

**6.1. Discovery and Nature of Gamma Radiation.** By allowing the collimated radiation from a sample of radium to pass through a perpendicular magnetic field, a certain portion of the radiation appeared to be undeflected. This undeflected beam was originally all called alpha radiation. In 1900, P. Villard[1] allowed this radiation to pass obliquely through a stack of photographic plates. Although much of the radiation was absorbed by the first layer, he found that some of it penetrated the entire stack of plates, tracing its path by activating every emulsion. Rutherford used a much stronger magnetic field and found that the more easily absorbed portion could be slightly deflected, indicating that it consisted of a stream of positively charged particles. There still remained the undeflected penetrating portion of the radiation. This was called gamma radiation and has been shown to consist of electromagnetic waves, identical in nature to very penetrating X-rays.

The wave-length of gamma rays was determined by the same technique used in evaluating the wave-length of X-rays. It was shown by Bragg that a wave-length $\lambda$ would be reflected by a crystal at a grazing angle of incidence $\theta$ if the lattice distance of the crystal $d$ satisfied the equation

$$\lambda = 2d \sin \theta \tag{6.1}$$

This method can be used for gamma rays with energies up to about 100 Kev. An experimental arrangement as used by

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[1] P. Villard, *Comptes Rendus*, **130**, 1178 (1900).

Rutherford [2] and Andrade is shown in Figure 6.1. The spectrogram reproduced [3] is actually that of the high energy "K" series lines from a heavy element. For very energetic gamma radiation the wave-length $\lambda$ becomes so small that no satisfactory crystal lattice exists capable of satisfying the Bragg law with an appreciably large reflecting angle $\theta$. In this energy region gamma rays are studied either by their absorption in specific elements such as lead, or by observing the behavior of recoil electrons, produced by the gamma rays, in electric or magnetic fields.

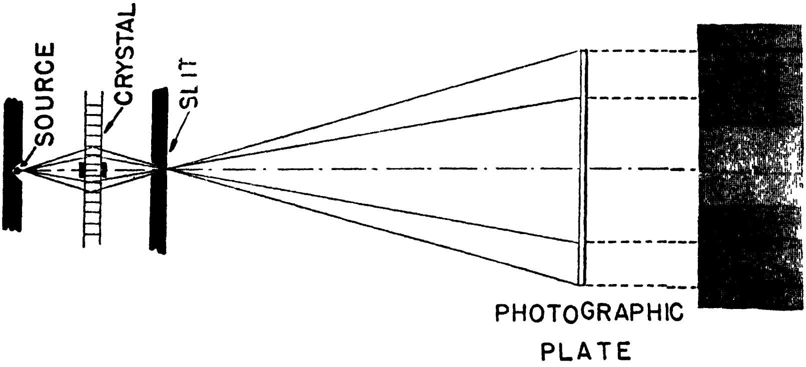

Fig. 6.1. A crystal spectrometer for gamma rays.

**6.2. Origin of Gamma Rays.** Gamma rays originate in the excited nuclei of atoms. They represent the energy difference between the initial excited state and a lower energy state which may or may not be the ground level. That is, between the initial and the ground states there may exist several possible energy levels. In such a case the original transition may be followed by one or more additional gamma emissions in rapid succession. The nucleus is finally left in the stable ground state. Selection rules may be formulated relating to the probability of a given transition, as is done for optical spectra. The packet of gamma radiation sent out as a consequence of a single transition is termed a "photon."

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[2] E. Rutherford and P. Andrade, *Phil. Mag.*, 28, 262 (1914).

[3] J. M. Cork, *Phys. Rev.*, 25, 197 (1925).

**6.3. The Photon.** In attempting to explain the observed form of the distribution curve of the radiant energy from a black-body, Planck, in 1901, introduced the notion of the atomicity of energy in absorption and emission processes.[4] In 1905, Einstein proposed the now famous "photoelectric equation." [5] This states that the energy $W$ of a light photon will on impact with an atom dislodge an electron and give it kinetic energy. The equation is

$$W = h\nu = \tfrac{1}{2}mv^2 + P \tag{6.2}$$

where $h$ is the Planck universal constant, $\nu$ is the frequency of the light, $m$ and $v$ are the mass and velocity of the ejected electron, and $P$ is the energy of binding of the electron or the work required to free it from the atom. It was seven years before this relationship was experimentally verified.[6]

In 1906, Einstein formulated further the corpuscular notion of light by stating: "Every quantity of energy of any form whatever represents a mass which is equal to this same energy divided by $c^2$, where $c$ is the velocity of light, and every quantity of energy in motion represents momentum." Thus the term photon applies to a wave-train or packet of electromagnetic radiation in motion, whose energy $W$ is

$$W = h\frac{c}{\lambda} = h\nu = mc^2 \qquad \text{(ergs)} \tag{6.3}$$

and whose momentum is

$$\frac{W}{c} = \frac{h}{\lambda} = \frac{h\nu}{c} = mc \qquad \text{(gm cm per sec.)} \tag{6.4}$$

The corpuscular notion of electromagnetic radiation was more firmly established by the striking experiments of A. H.

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[4] M. Planck, *Ann. d. Phys.*, **4**, 552 (1901).

[5] A. Einstein, *Ann. d. Phys.*, **17**, 132 (1905).

[6] K. T. Compton, *Phil. Mag.*, **23**, 579 (1912); A. L. Hughes, *Phil. Trans. Roy. Soc.*, **212**, 205 (1912); R. A. Millikan and J. Wright, *Phys. Rev.*, **36**, 68 (1912).

Compton in what is now termed the "Compton effect," which will be described later.

**6.4. The Absorption of Gamma Radiation.** While alpha radiation is usually completely absorbed in a fraction of a millimeter of aluminum and beta rays are absorbed by a few millimeters of the same metal, gamma rays may traverse a thickness of several centimeters. The absorption of gamma radiation by materials of different density is found to vary almost directly with the density. If radiation of intensity $I$ is incident upon an absorbing layer of thickness $dx$, the amount of radiation absorbed, $dI$, is proportional both to $dx$ and to $I$, so that

$$dI = -\mu I \, dx \tag{6.5}$$

The proportionality factor $\mu$ is a characteristic property of the medium. It is called the coefficient of absorption. It may be defined as the relative loss in intensity per centimeter of path. The negative sign indicates that $I$ decreases as $x$ increases. It follows from equation 6.5, by integration, that

$$\log_e I = -\mu x \tag{6.6}$$

By evaluating at the limits, $I = I_0$ when $x = 0$, and $I = I$ at $x = x$, the emergent intensity $I$ is

$$I = I_0 e^{-\mu x} \tag{6.7}$$

The coefficient of absorption $\mu$ may be expressed as the reciprocal of the thickness that will reduce the intensity of an incident beam to $1/e$ or $1/2.73$ of its original value. To reduce the intensity to half its original value a thickness $x_{1/2}$ called the half-value thickness is required. From equation 6.7 it then follows that

$$\log_e \frac{I_0}{I} = \log_e 2 = 0.693 = \mu x_{1/2} \tag{6.8}$$

and

$$\mu = \frac{0.693}{x_{1/2}} \tag{6.9}$$

Experimentally, the half-value thickness is easy to determine, and from this the absorption coefficient $\mu$ is expressed by equation 6.9. The specimen under study is placed above an ionization chamber and the intensity $I$ of the radiation is noted as the thickness of an interposed absorber is increased. The data are represented on a log $I$ versus thickness coordinate plot. A straight line of negative slope will result if the gamma radiation is of single value as to energy. In case two discrete gamma rays are present the resulting curve may be analyzed to yield the absorption coefficient of each, provided the radiation is sufficiently intense to be followed through a very thick layer of absorbing substance and the two gamma rays have appreciably different absorption coefficients.

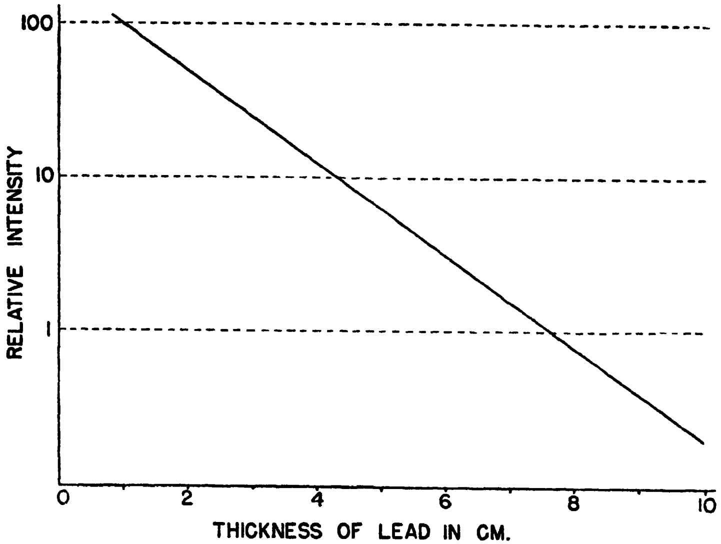

FIG. 6.2. The decrease in intensity of the gamma radiation from zinc 65 in lead.

In Figure 6.2 is shown the absorption of the gamma rays from a radioactive isotope of zinc of mass 65. From the linear curve the half-value thickness is 1.022 cm so that $\mu$ is .693/1.022 or 0.678 $\text{cm}^{-1}$. It is sometimes desirable to divide the linear coefficient $\mu$ by the density of the substance $\rho$, giving what is termed the "mass absorption" coefficient $\mu/\rho$. This is thus the reciprocal of that number of grams per cm$^2$ that will reduce the intensity to $1/e$ of its original value. The same value would be found for the mass absorption coefficient for a substance regardless of its state of aggregation, that is, as gas, liquid, or solid.

On dividing the mass absorption coefficient by $(N)$, the number of atoms per gram, an atomic absorption coefficient $\mu_a$, defined as the relative absorption per atom, results. On dividing further by the atomic number $Z$, an "electronic absorption" coefficient $\mu_e$ or the relative loss in intensity per electron is obtained. Since the absorption of gamma radiation is an electronic phenomenon it might be expected for a given energy that the latter quantity $\mu_e$ would be the same regardless of the element from which it was derived. In practice this is not the case, but the electronic absorption depends upon the binding of the electron. For gamma radiation of energy 1.3 Mev, the linear, mass, and electronic absorption coefficients in different absorbers are shown in Table 6.1.

TABLE 6.1

| *Absorber* | $\mu (cm^{-1})$ | $\frac{\mu}{\rho}\left(\frac{cm^2}{gm}\right)$ | $\mu_e = \frac{\mu}{\rho NZ}$ |
|---|---|---|---|
| Carbon | .115 | 0.059 | $1.96 \times 10^{-25}$ |
| ✓ Aluminum | .156 | 0.058 | $2.00 \times 10^{-25}$ |
| Iron | .455 | 0.058 | $2.06 \times 10^{-25}$ |
| ✓ Copper | .509 | 0.057 | $2.08 \times 10^{-25}$ |
| Tin | .345 | 0.060 | $2.36 \times 10^{-25}$ |
| ✓ Lead | .800 | 0.071 | $2.98 \times 10^{-25}$ |

It is apparent that the more tightly bound the electron, the greater its ability to reduce the intensity of the gamma radiation.

The loss in energy suffered by gamma radiation in its passage through matter follows from three separate effects, namely, the "photoelectric" effect, the "Compton" effect and "pair production." These will be treated in order.

**6.5. The Photoelectric Effect.** It was early known that the passage of gamma radiation through a gas rendered the gas electrically conducting. This meant that ions were produced by the gamma rays. Such ions can be readily visualized as negative orbital electrons dislodged from the atoms of the gas. The heavy atomic residues will persist only a short time as positive ions because they will soon capture other electrons. In case the gamma ray gives all its energy to the dislodged electron, the electron is termed a photoelectron. The energy balance applicable to this case was first proposed by Einstein.[7] The energy of the incident photon

$$h\nu = P + \tfrac{1}{2}mv^2 \tag{6.10}$$

where $h$ is the Planck constant, $\nu$ is the frequency of the radiation, $P$ is the binding energy of the electron in the atom, $m$ is its mass, and $v$ its velocity. Since gamma rays are usually very energetic, their energy is large compared to the binding energy $P$. Hence the kinetic energy of the ejected electron is not much less than that of the photon. Absorption due to the photoelectric process is greater, the more tightly bound the electron. Thus in a given element, a "K" electron may be many times as effective as an "L" electron in stopping gamma radiation. Likewise for a gamma ray of given energy, the absorption per "K" electron increases rapidly with the atomic number of the absorbing element. For heavy elements and radiation of low energy the photoelectric effect accounts for most of the absorption.

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[7] A. Einstein, *Ann. d. Phys.*, 17, 132 (1905).

On treating the absorption of gamma rays having energies up to 0.5 Mev in light elements, Sauter[8] developed a theoretical expression for the photoelectric atomic absorption coefficient $\tau_{ph}$. It was shown to be related to the atomic number $Z$, and to the binding energy $P$ as

$$\tau_{ph} = c\,\frac{Z^5}{P} \quad \checkmark \qquad (6.11)$$

where $c$ is a calculable constant, approximately $23 \times 10^{-40}$, and $P$ is the binding energy in ergs. More detailed developments capable of being extended to the heavy elements and high energies have been made.[9] These are still in part empirical to suit the experimental data.[10] Heitler[11] concludes that for the most extreme case, namely using lead as absorber and exceedingly high energy photons, the photoelectric absorption coefficient is about 2.2 times the value expected by equation 6.11.

At impact the conservation of momentum must be maintained. A photon of energy $h\nu$ possesses a momentum $h\nu/c$. If the binding energy were zero it would be impossible for the photon to communicate its entire energy to an electron, for obviously both conservation of energy and momentum could not be satisfied.

By the former,

$$h\nu = \tfrac{1}{2}mv^2 \quad \checkmark \qquad (6.12)$$

and by the latter,

$$\frac{h\nu}{c} = mv \qquad (6.13)$$

so that by dividing equation 6.12 by 6.13, $v = 2c$, which is an absurdity.

It must therefore follow that the heavy residue of the atom shares in the impact by carrying off much of the momentum and little of the energy. As a result the angular distribution of the emitted photoelectrons can be calculated. For low energy photons, no photoelectrons will be emitted in the forward direction of the gamma quanta. A photoelectron has the greatest probability of being emitted in the direction of polarization of the incident quantum, that is, at right angles to its forward direction. As the energy increases, the tendency is for the photoelectrons to have a forward component of velocity. In Figure 6.3 the distribution of electrons is shown at various angles when their energies are low and also when their velocities are of the order of one-third that of light.[12]

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[8] F. Sauter, *Ann. d. Phys.*, **11**, 454 (1931).

[9] H. Hall, *Phys. Rev.*, **45**, 620 (1934).

[10] H. R. Hulme, J. McDougall, R. Buckingham, and R. Fowler, *Proc. Roy. Soc.*, **149** 131 (1935).

[11] W. Heitler, *The Quantum Theory of Radiation*, Clarendon Press, p. 126 (1935).

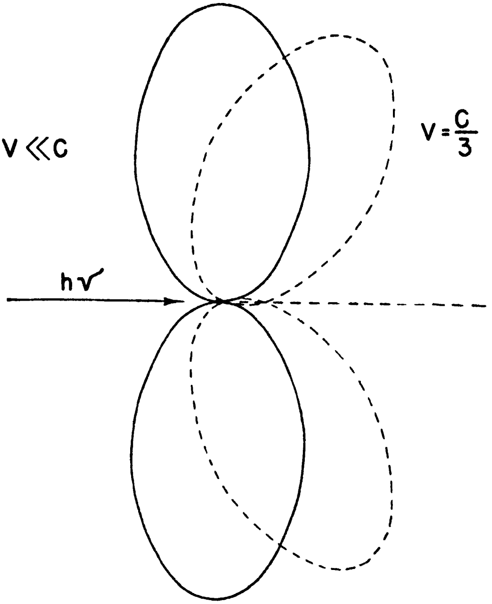

FIG. 6.3. The distribution of photoelectrons of low energy and higher energy.

To determine the energy of a gamma ray by the photoelectric effect some success has been attained by the use of a Wilson cloud chamber.[13] The chamber is provided with a thin lead foil within the sensitive volume. A strong magnetic field is applied and the photoelectrons ejected from the foil trace out circular tracks. The radii of curvature of the tracks in centimeters and the magnetic induction $B$ in gauss, yield the momenta of the photoelectrons and hence their energy. From this the energy $W$ of the gamma ray can be computed by adding the characteristic binding energy.

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[12] W. Heitler, *op. cit.*, p. 123.

[13] J. R. Richardson, *Phys. Rev.*, 53, 124 (1938); 55, 609 (1939).

**6.6. The Compton Effect.** In 1922, a very important experimental observation was made by A. H. Compton.[14] Quite independent of the photoelectric effect, it was shown beyond any doubt that photons must be considered as corpuscles, in that they exhibit mass and momentum as do ordinary material particles. In the "Compton effect" the photon of wave-length $\lambda$ or frequency $\nu$ with the velocity $c$, is incident upon a free or loosely bound electron. At impact, the electron recoils with a velocity $v$ at some angle $\phi$ with the direction of the

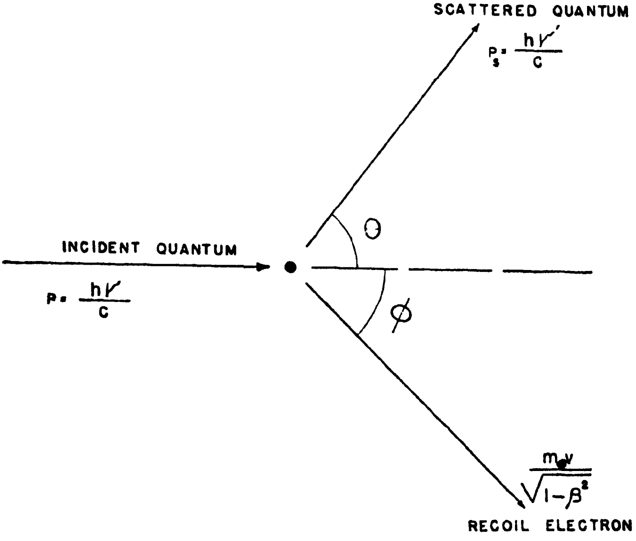

Fig. 6.4. Compton scattering.

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[14] A. H. Compton, *Phys. Rev.*, 21, 482 (1923); *Bull. Nat. Res. Counc.*, 20, 10 (1922).

photon, as shown in Figure 6.4. The incident photon surrenders its identity and a new photon of lesser energy and frequency $\nu'$ is ejected at a direction $\theta$ with the original photon.

Denoting the rest mass of the electron as $m_o$, then by relativity its mass, $m$, momentum, and energy are respectively

$$m_o(1-\beta^2)^{-\frac{1}{2}}, \quad m_o v(1-\beta^2)^{-\frac{1}{2}}, \quad \text{and} \quad (mc^2 - m_o c^2)$$

where $\beta$ is the ratio of its velocity $v$ to that of light $c$. The similar quantities for the photon are respectively

$$\frac{h\nu}{c^2}, \quad \frac{h\nu}{c}, \quad \text{and} \quad h\nu$$

From the conservation of energy, and the conservation of momentum in directions both parallel and perpendicular to the incident photon, three independent equations may be written as

$$h\nu = h\nu' + mc^2 - m_o c^2 \tag{6.14}$$

(parallel)

$$\frac{h\nu}{c} = \frac{m_o v}{\sqrt{1-\beta^2}} \cos\phi + \frac{h\nu'}{c} \cos\theta \tag{6.15}$$

(perpendicular)

$$\frac{m_o v}{\sqrt{1-\beta^2}} \sin\phi = \frac{h\nu'}{c} \sin\theta \tag{6.16}$$

The classical solution of these equations, which was of particular interest in X-ray spectroscopy, gave the change in wave-length on scattering as

$$\lambda' - \lambda = 0.0241(1 - \cos\theta)(\text{Å.U.}) \tag{6.17}$$

or

$$\delta\lambda = 0.0482 \sin^2\frac{\theta}{2}\,(\text{Å.U.}) \tag{6.18}$$

It is apparent that the change in wave-length at a given angle is independent of the incident energy. In the forward direction, $\theta = 0$, so that there is no loss in energy by the photon.

For each scattered photon at an angle $\theta$, there is a particular recoil particle at an angle $\phi$. The relationship between these particles, as $\theta$ takes all values from zero up to $\pi$, is shown by Figure 6.5. For a photon scattered directly backward, the recoil electron must go directly forward. Since

$$\lambda = \frac{hc}{W} \quad \text{and} \quad \lambda' = \frac{hc}{W'}$$

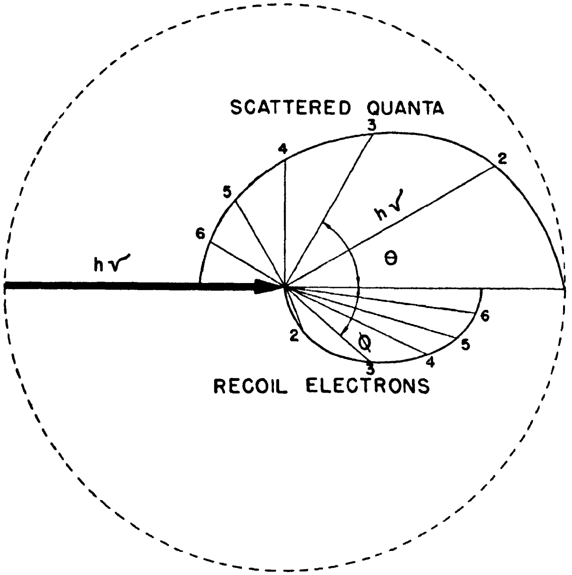

Fig. 6.5. The scattered quanta and recoil electrons in "Compton" scattering.

where $W$ and $W'$ are the photon energies before and after scattering, it follows that

$$\lambda' - \lambda = hc\left(\frac{1}{W'} - \frac{1}{W}\right) = 0.0482 \qquad (6.19)$$

so that

$$W' = \frac{W}{1 + 3.9W} \qquad (6.20)$$

where $W$ is expressed in Mev.

The energy of a gamma ray may be found by observing the Compton electrons proceeding in the forward direction of the original beam from a thin scattering foil placed in a Wilson cloud chamber.[15] For this purpose foils of aluminum or carbon are used and only those tracks in a small solid angle are selected. By noting the radius of curvature of the track in a known magnetic field it is possible to evaluate the energy of the recoil Compton electron. This value which is $(W - W')$ can then be used in equation 6.20, to yield the energy $W$ of the incident photon.

This process of Compton scattering is effective in reducing the intensity of a beam of gamma radiation traversing matter. It is particularly important in the lighter elements for energies that are not too high. For example, it is the main contributing factor to the total absorption coefficient in such elements as copper, for energies up to 3 Mev.

The scattering of radiation by electrons has been calculated by Thomson from classical theory.[16] He considered that each electron on being swept by the radiation would be accelerated by the electric field of the electromagnetic wave. As a result the electron would in turn radiate a wave and the combined effect for all of the electrons would lead to a scattering coefficient $\sigma$. The expression obtained for $\sigma$ for $N$ electrons per cm$^3$ was

$$\sigma\ (\text{cm}^3) = \frac{8\pi}{3}\frac{e^4}{m^2c^4}N \tag{6.21}$$

To obtain the scattering for a single electron this is divided by $N$ and it can be numerically evaluated as

$$\sigma\ (\text{electron}) = 6.60 \times 10^{-25} \tag{6.22}$$

This is the probability that a single electron per cm$^3$ will scatter a single photon passing through the volume. It might be termed therefore the "cross section" of the electron for photon-electron collision and as such can be expressed in cm$^2$. The frequency of the scattered radiation is the same as that of the incident photon and the scattering should be independent of the energy.

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[15] J. R. Richardson and F. Kurie, *Phys. Rev.*, 50, 999 (1936).

[16] J. J. Thomson, *The Conduction of Electricity through Gases*, 2nd ed., Longmans, Green & Co., p. 325 (1906).

The Thomson formula was found to be inadequate for scattering in which the electron carries off any fraction of the energy. A later development based upon quantum mechanics was carried out in 1929 by Klein and Nishina.[17] Although somewhat complicated, the result can be simplified for special limiting cases. For very low energies the result is similar to the classical expression of Thomson. For very high energies the expression may be put in the following form:

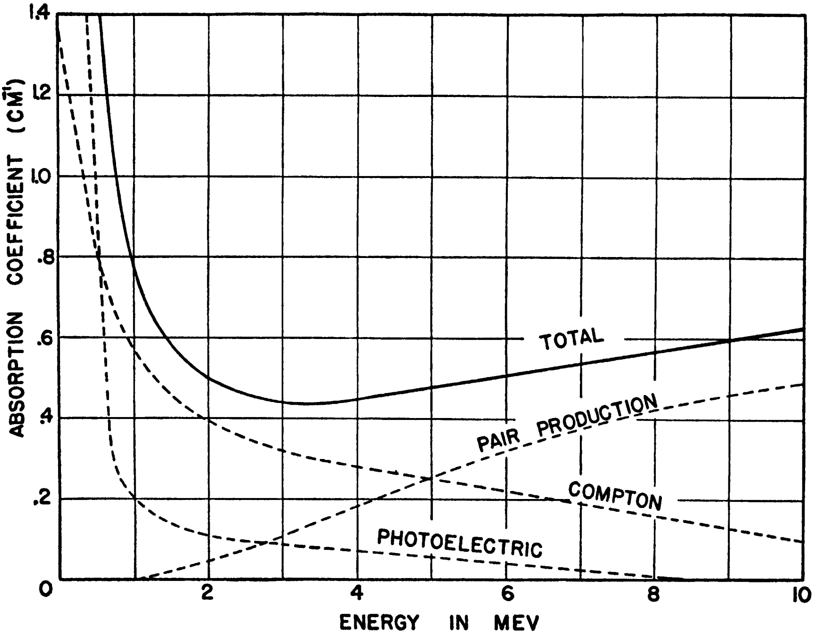

Fig. 6.6. The absorption of gamma radiation in lead.

$$\sigma \text{ (electron)} = \frac{a}{\nu}\left[\frac{1}{2} + \log bW\right] \tag{6.23}$$

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[17] O. Klein and Y. Nishina, *Zeits. f. Phys.*, 52, 852 (1929).

where $a$ and $b$ are constants, $\nu$ is the frequency, and $W$ is the energy of the gamma photon. It is thus evident that the scattering coefficient varies inversely with the energy of the photon. The angular distribution of the scattered radiation from a collection of electrons can be formulated, leading to a rather involved expression. This contribution to the total absorption coefficient as calculated by Heitler is shown for lead in Figure 6.6.

**6.7. Pair Production.** By 1932 many measurements of absorption coefficients had been made for high energy gamma rays in such elements as aluminum, copper, and lead. The observed absorption coefficients[18] were found to be larger than would be expected from the combined Compton scattering and photoelectric effect. This discrepancy was at first usually explained as due to some unknown contribution to absorption by the nuclei.

In 1934 Dirac outlined a relativistic theory of the electron.[19] In the development along with the ordinary states of positive energy, he was led to the notion of the existence of negative energy states. These possible negative energy states were assumed to be normally filled with electrons and not observable. A gamma ray might remove one of these electrons of negative energy so that it became a negative electron. The "hole" remaining would appear as a positively charged particle. It was at first considered by Dirac that this particle should be a proton.

In 1933 Anderson discovered that cosmic radiation in passing through a vertical cloud chamber, equipped with a very strong magnetic field, showed many tracks due to negatively charged particles.[20] Occasionally, however, tracks were noticed whose curvature indicated that they were made by positively charged particles. After eliminating the possibility that these tracks were made by reflected electrons as shown in Figure 5.4*A*, Anderson announced that they must be due to protons. On further investigation of the curvature of the tracks, together with the specific ionization along the path, he concluded that the particles must really be positive electrons or "positrons." With each positron there always appeared at least one negative electron. This is what would be expected if the incident gamma ray is annihilated, giving rise to an electron "pair."

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[18] C. Y. Chao, *Proc. Nat. Acad.*, **16**, 431 (1930); L. Meitner and H. Hupfeld, *Zeits. f. Phys.*, **27** (1931); L. H. Gray, *Proc. Camb. Phil. Soc.*, **27**, 103 (1931); W. Gentner, *Jour. de Phys. et rad.*, **6**, 340 (1935).

[19] P. Dirac, *Proc. Camb. Phil. Soc.*, **30**, 150 (1934); see also W. Furry and J. R. Oppenheimer, *Phys. Rev.*, **45**, 245 (1934), and H. Bethe and W. Heitler, *Proc. Roy. Soc.*, **146**, 83 (1934).

[20] C. D. Anderson, *Phys. Rev.*, **43**, 494 (1933).

In the annihilation process momentum and energy must be conserved. It therefore follows that an atom must participate in the event in order to carry off the excess momentum, for otherwise it is impossible to satisfy the conservation equations. Hence pair production can occur only in the presence of matter, and the heavier the atom, the greater the probability of gamma conversion in this way. If $m$ is the mass of the electron and $c$ the velocity of light, then for the creation of the positron and the electron an energy of $mc^2$ (0.511 Mev) must be supplied for each, or in total 1.022 Mev.

By irradiating a lead foil in a cloud chamber with gamma rays having energies well above 1 Mev, the phenomenon of pair production may be readily observed.[21] By noting the radii of curvature, the energy of each particle may be determined and their sum used to evaluate the energy of the gamma ray. Such a pair is shown in Figure 5.4*B*. The gamma energy is 1.022 Mev plus the total energy of the particles. The probability of this process has been calculated, resulting in a rather complicated expression when the energies of the gamma rays extend over a wide range.[22] The probability of pair formation increases as the square of the atomic number $Z$ of the radiated element, and increases with the incident energy.

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[21] I. Curie and F. Joliot, *Comptes Rendus*, **196**, 1581 (1933); J. Chadwick, P. Blackett, and G. Occhialini, *Proc Roy. Soc.*, **146**, 83 (1934).

[22] J. G. Jaeger and H.. Hulme, *Proc. Roy. Soc.*, **153**, 443 (1935).

**6.8. Total Absorption.** Since the absorption due both to the Compton effect and to the photoelectric effect decreases as the energy increases, while the contribution due to pair production increases with increasing energy, it follows that at some intermediate energy the total absorption coefficient for any element exhibits a minimum value. For lead, the minimum occurs for gamma rays with an energy of about 3.5 Mev, whereas in copper and aluminum minimum absorption occurs at about 10 Mev and 22 Mev, respectively.

For the absorption in lead, Heitler has computed the contribution to the total absorption coefficient, made by each of the three effects, over a wide range in energy. These data are shown graphically in Figure 6.6. The minimum absorption coefficient for lead as calculated has a value of 0.46 cm$^{-1}$. There is experimental evidence[23] that the true coefficient of absorption is smaller than this calculated value. Should this prove to be the case the discrepancy will probably be found in the Klein-Nishina calculation at high energies.

The over-all absorption coefficient is quite different from that which would have been expected by extrapolating the variation of absorption coefficient with energy, from the X-ray region. For the mass absorption coefficient of X-rays Allen has proposed a relationship of the form

$$\mu/\rho = a\lambda^{2.92} + b \qquad (\mathrm{gm}^{-1}\ \mathrm{cm}^2) \qquad \mathbf{(6.24)}$$

where for aluminum $a$ and $b$ were constants whose values were respectively 14 and 0.16 when $\lambda$ is the wave-length in Ångstrom units.[24] For other elements, $a$ and $b$ have different values.

**6.9. Gamma Spectra and Internal Conversion.** There is good evidence that the gamma rays sent out by a radioactive source consist of definite discrete energies. The energies may be experimentally determined in any of several ways. If only one or two gamma energies are present they may be determined by noting their absorption coefficient in various materials such

[23] J. M. Cork, *Phys. Rev.*, 67, 53 (1945).
[24] S. J. Allen, *Phys. Rev.*, 28, 907 (1926).

as copper or lead and making reference to curves relating energy and absorption as is done in Figure 6.6.

Other methods involve the observation and measurement of the energy of recoil electrons excited by the gamma ray. These may be either photoelectrons or "Compton" recoil electrons or "pair" electrons. They may be studied in a cloud chamber or a beta ray spectrometer. The spectrometer may be a semicircular magnetic or an electron lens type or it may make use of electrostatic focusing.

It frequently happens that a gamma ray in its passage out from the nucleus through the orbital electrons, will give up its entire energy to an electron of the same atom in which it originated. This process is called "internal conversion." The electrons that are most likely to participate in this conversion are the tightly bound "K" electrons. In some radioactive emissions the probability of this conversion seems to approach unity. For a gamma ray of definite energy coming from a collection of atoms, some atoms will eject "K" electrons, others "L" electrons, and some "M" electrons. The kinetic energy of these electron groups will differ from the energy of the gamma ray by the binding energy of each group. Such a distribution of conversion electrons is shown in Figure 6.7.[25]

In this figure the three peaks correspond to the K, L, and M electron groups ejected by a single gamma ray (0.276 Mev) from an isotope of lanthanum, produced by bombarding barium with deuterons. With the precision now available in beta ray spectroscopy the K-L or K-M differences may be obtained with sufficient accuracy to identify the atomic number of the radiating isotope.

The possibility of internal conversion had been suggested by Rutherford in 1917.[26] Experimental evidence to confirm its existence in some of the natural radioactive emitters was presented by Ellis in 1921.[27]

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[25] J. M. Cork and G. Smith, *Phys. Rev.*, **60**, 480 (1941).
[26] E. Rutherford, *Phil. Mag.*, **34**, 153 (1917).
[27] C. D. Ellis, *Proc. Roy. Soc. A*, **99**, 261 (1921).

The relative areas of "K," "L," and "M" peaks are of theoretical interest in determining the probability of the reaction. Unfortunately only gamma rays with energies less than about 400 Kev offer sufficiently high yields of conversion electrons to make their measurement possible. Subsequent observations have revealed that the phenomenon is fairly common. Several examples designated by the letter "I" may be noted in the table of isotopes shown in Chapter XII. The theoretical treatment of internal conversion in light elements has been the subject of many reports.[28]

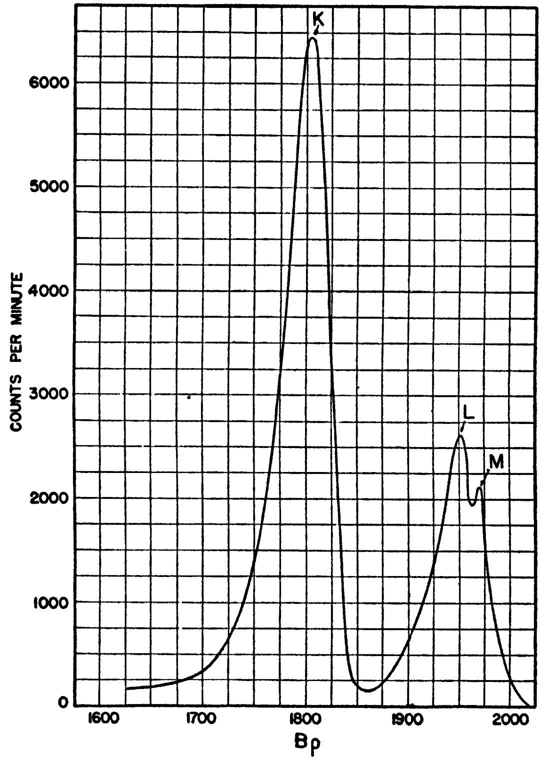

Fig. 6.7. Internally converted gamma rays from lanthanum.

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[28] S. Dancoff and P. Morrison, *Phys. Rev.*, 55, 133 (1939); M. Hebb and E. Nelson, *Phys. Rev.*, 58, 486 (1940); R. J. Bessey, Thesis (1942), University of Michigan.

**6.10. Nuclear Transmutation by Gamma Rays—Photodisintegration.** On allowing the gamma radiation from thorium C, whose energy is about 2.62 Mev, to irradiate deuterium gas, Chadwick and Goldhaber found evidence of nuclear disintegration.[29] It appeared that the deuterium atom ${}_1\mathrm{H}^2$ split up, under the action of the gamma ray, into a proton ${}_1\mathrm{H}^1$ and a neutron ${}_0n^1$. This process has been termed "photodisintegration."

The energy of the proton produced in the disintegration may be measured by the use of a linear amplifier or by a cloud chamber. Assuming that the neutron carries approximately the same amount of energy, then the binding energy of the deuteron can be computed, if that of the incident gamma ray is known.

The masses of the respective particles are shown in equation form as

$$\begin{array}{c} {}_1\mathrm{H}^2 \rightarrow {}_1\mathrm{H}^1 + {}_0n^1 + Q \\ 2.014722 \rightarrow 1\ 008130 + 1.00893 - 0\ 00234(-2.178 \text{ Mev.}) \end{array} \tag{6.25}$$

indicating that an energy $Q$ must be supplied equivalent to a mass deficiency of 0.00234 mass units or 2.178 million electron volts. For gamma energies less than 2.178 Mev no photodisintegration should occur in deuterium. Actually the mass of the neutron is known only through the observation of this gamma ray threshold. More recent measurements of Wiedenbeck place the photodisintegration threshold of deuterium at 2.185 ± 0.006 Mev.

The cross section for the photodisintegration process as expressed by Chadwick and Goldhaber was about $6 \times 10^{-28}$ cm$^2$. Although this is a small quantity the great penetration of gamma radiation brings into the exposure a correspondingly large number of nuclei, so that the number of disintegrations is appreciable.

For gamma rays of low energy $h\nu$, incident on a nucleus whose binding energy is $W$, the cross section, $\sigma$ has been expressed [30, 31] as

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[29] J. Chadwick and M. Goldhaber, *Proc. Roy. Soc.*, **151**, 479 (1935); see also M. Wiedenbeck and C. Marhofer, *Phys. Rev.*, **67**, 54 (1945).

$$\sigma = \frac{4}{3}\frac{he^2}{mcW}\frac{\left(\frac{h\nu}{W} - 1\right)^{3/2}}{\left(\frac{h\nu}{W}\right)^3} \tag{6.26}$$

At the maximum value of $\sigma$, as the energy $h\nu$ is varied, the differential $\frac{d\sigma}{d(h\nu)} = 0$. It follows from the differentiation of equation 6.26, that under this condition, $h\nu = 2W$. Thus the greatest probability of photodisintegration occurs when the gamma energy is just twice that of the binding energy. From an energy point of view the process is reversible. The capture of a thermal neutron in hydrogen produces a deuterium nucleus and is accompanied by the release of a gamma photon of 2.17 Mev.

The gamma rays from lithium bombarded with protons have an energy in excess of 17 Mev. These gamma rays have been shown to be able to produce photodisintegrations in practically all of the elements of the periodic table.[32] Since a neutron is ejected in the process the product nucleus is always less in mass by unity than the bombarded nucleus. If the product nucleus does not normally exist in nature it will be radioactive, and will in general be found to be a positron emitter.

With the high energy X-rays or gamma radiation now available from accelerating devices such as the 100 Mev betatron of the General Electric Co., photodisintegration has been greatly extended. It has been found that many particles may be evaporated from the highly excited nucleus with a greater probability than the emission of a single particle carrying a large energy. By irradiating oxygen 16 there appears to be

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[30] H. Bethe and R. Peierls, *Int. Conf. on Phys.*, London (1934); *Phys. Rev.*, **47**, 747 (1935).

[31] G. Breit and E. Condon, *Phys. Rev.*, **49**, 904 (1936).

[32] W. Bothe and W. Gentner, *Zeits. f. Phys.*, **106**, 236 (1937).

good evidence that along with other products carbon 11, whose half-life is 20.7 minutes, is produced. This would involve the escape of 2 protons and 3 neutrons.

**6.11. Ionization Chambers for Gamma Radiation.** Since gamma rays eject electrons from some of the atoms they traverse, they have an ionizing effect. In air under normal conditions of pressure and temperature, on the average each of a group of high energy photons will produce from one to two ion pairs per cm of path. Some photons will disappear entirely, while others are only modified by the Compton reaction. Each high energy particle that is formed may in turn produce along its path fifty times as many ions per cm, hence the recoil electrons produced by the gamma rays are responsible for the total ionization. The ionization in a gas increases with the pressure and with the molecular weight of the gas. For this reason argon gas at pressures up to many atmospheres is often used advantageously in ionization chambers. Other gases such as sulphur hexafluoride ($SF_6$), methyl bromide, or freon ($CCl_2F_2$), whose molecular weights are 146, 94.9, and 120.9, are frequently used. The latter is a commonly used refrigerant and because of its low boiling point (−28° C.) and chemical inactivity is very satisfactory.

Gamma rays give rise to many recoil electrons from the walls of an ionization chamber. This effect has sometimes been utilized to increase enormously the sensitivity of an ionization chamber. By the use of thin metal foils alternately charged positively and negatively, the metal surface exposed to the gas and hence the sensitivity may be multiplied by a large factor.

**6.12. The Gamma Rays from Radium and Thorium (C + C′).** Gamma rays whose energies are less than 400 Kev may be evaluated by their internal conversion electrons. For gamma rays of greater energy, Compton electrons and photoelectrons serve to indicate the energy. Above 1.02 Mev, that is $2mc^2$, pair production may be utilized to evaluate effectively the gamma energies. When pair-production occurs in a magnetic

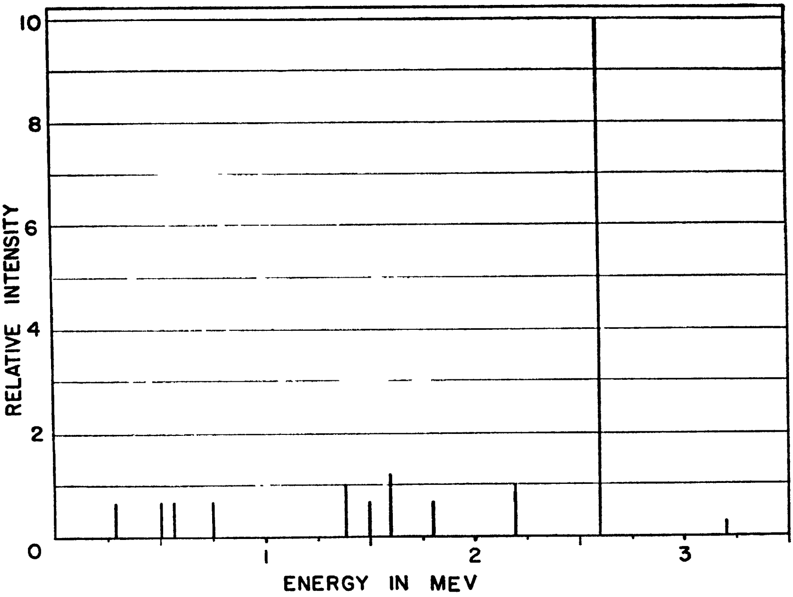

FIG. 6.8. The gamma spectrum from thorium (C + C′).

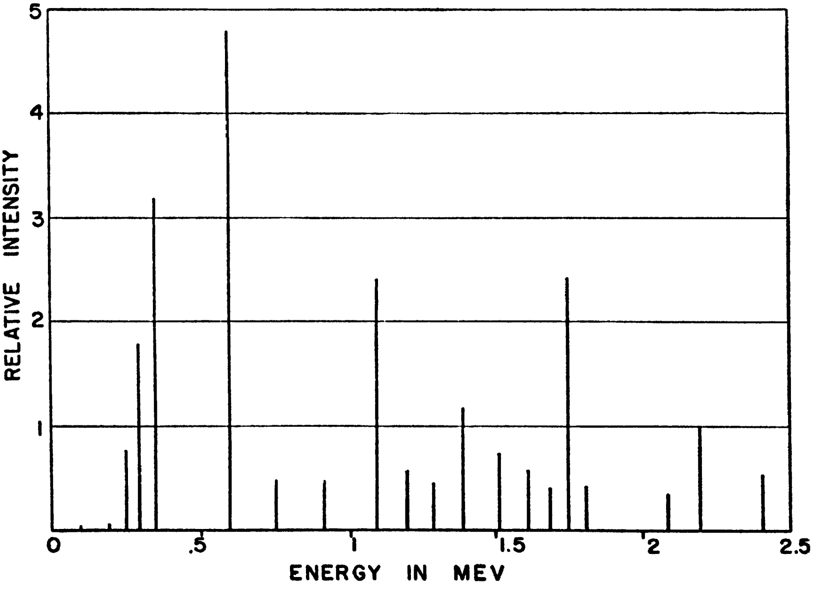

FIG. 6.9. The gamma spectrum from radium.

spectrometer, observations may be made on either the positrons or the negative electrons as desired, by reversing the magnetic field. By using the positrons any confusion due to other accompanying electrons is avoided. The high energy spectra emitted by radium and by thorium (C + C′) have been carefully studied in this way. These spectra are of interest since these sources have been so extensively used in gamma

TABLE 6.2. THE GAMMA RAYS FROM TH (C + C′) ABOVE 1 MEV

| *Energy (Mev)* | *Relative Intensity* |
|---|---|
| 1.35 | 1.0 |
| 1.50 | 0.65 |
| 1.60 | 1.10 |
| 1.80 | 0.65 |
| 2.20 | 0.60 |
| 2.62 | 10.00 |
| 3.20 | 0.25 |

TABLE 6.3. GAMMA RAYS FROM RADIUM

| *Energy (Mev)* | *Relative Intensity* |
|---|---|
| 1.10 | 2.4 |
| 1.21 | 0.56 |
| 1.29 | 0.44 |
| 1.39 | 1.19 |
| 1.52 | 0.71 |
| 1.62 | 0.54 |
| 1.69 | 0.40 |
| 1.75 | 2.4 |
| 1.82 | 0.41 |
| 2.09 | 0.37 |
| 2.20 | 1.0 |
| 2.42 | 0.5 |

ray studies. The distribution of photons in the high energy spectrum of thorium (C + C′) is shown in Figure 6.8,[33] and those from radium in Figure 6.9.[34] The data are presented numerically in Tables 6.2 and 6.3.

**6.13. Use of Gamma Radiation in Radiology.** Any sufficiently intense ionizing agent will kill living tissue. Those cells that are in the process of growth, such as most cancerous tissue, are usually more susceptible. It is the hope of the radiologist that by proper dosage the abnormal fast-growing tissue may be destroyed without seriously damaging normal cells. Therapeutic doses used in practice vary from 300 up to 3000 roentgen units. The filtered gamma radiation at a point 10 cm from a source of one gram of radium in one hour is about 85 roentgen units. The absorption coefficient of tissue for the gamma radiation from radium is about 0.067 $\text{cm}^{-1}$. The radiation thus has a very considerable penetration, losing about 7% of its intensity on passage through each centimeter of tissue or dropping to half-value on traversing a layer of 8 cms.

**6.14. The Wave-Nature of Particles.** With the elaboration of the photoelectric and the "Compton" effects, the dual nature of electromagnetic radiation was well established, namely that it is both wavelike and corpuscular. It was soon equally well established that such entities as electrons, protons, and neutrons must be regarded not only as corpuscular but also as wavelike in nature.

The first evidence of this was presented by the famous electron scattering experiments of Davisson and Germer in 1925.[35] By using as the scatterer a crystal of nickel, they found certain well-defined beams of electrons issuing from the target for a certain definite incident angle. The theory sufficient to explain their results as a Bragg crystal reflection had already been formulated, but was unknown to the experimenters. In 1924, L. de Broglie had proposed in a Doctor's thesis that the particles of matter are intrinsically wavelike as well as corpuscular in nature.[36] The theory of de Broglie has been extended by Scrödinger,- Heisenberg, and others to become the extensive subject of "Wave-Mechanics."

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[33] A. Alichanow and G. Latyschev, *Jour. Phys.* USSR, **3**, 263 (1940).

[34] A. Alichanow and V. P. Dzelepov, *Comptes Rendus*, USSR, **20**, 133 (1938).

[35] C. J. Davisson and L. H. Germer, *Phys. Rev.*, **30**, 705 (1927).

The energy $W$ of a particle was considered associated to a frequency $\nu$ just as for a photon, namely $W = h\nu$ or $\frac{hc}{\lambda}$ where $h$ is the Planck constant, $c$ the velocity of light, and $\lambda$ is the wave-length. The momentum $P$ is the energy $W$ divided by the velocity of light $c$, hence

$$P = mv = \frac{h\nu}{c} = \frac{h}{\lambda} \tag{6.27}$$

Thus there results a wave-length $\lambda$ given by

$$\lambda = \frac{h}{mv} \tag{6.28}$$

If the particle derives its energy $W$ from the acceleration of a charge $e$ in falling through a potential $E$, then,

$$W = Ee = \tfrac{1}{2}mv^2 \tag{6.29}$$

as that

$$v = \sqrt{\frac{2Ee}{m}} \tag{6.30}$$

and

$$\lambda = \frac{h}{m\sqrt{\frac{2Ee}{m}}} = \frac{h}{\sqrt{2eEm}} \tag{6.31}$$

For electrons

$$\lambda = \frac{6.624 \times 10^{-27}}{\sqrt{2 \times 4.8025 \times 10^{-10} \times 9.1066 \times 10^{-28} \times \frac{1}{300}} \times \sqrt{E}}$$

$$= \frac{12.2}{E^{1/2}} \times 10^{-8} \text{ cm} \tag{6.32}$$

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[36] L. de Broglie, Theses, Paris, Mason et cie. (1924); *Ann. d. Phys.*, 3, 22 (1925).

For protons

$$\lambda = \frac{12.2 \times 10^{-8}}{\sqrt{1838E}} = \frac{28.6}{E^{1/2}} \times 10^{-10}\ \text{cm} \qquad (6.33)$$

so that at 9 Mev the wave-length of protons becomes $9.5 \times 10^{-13}$ cm, which is approaching in magnitude the dimensions of the nuclear diameter. For very slow protons or thermal neutrons the de Broglie wave-length becomes of such an order that Bragg crystal reflection is entirely possible.

## QUESTIONS AND PROBLEMS

**1.** The intensity of a beam of gamma rays on passage through lead of thicknesses 1, 3, 5, and 7 cms is found to be 90, 20.6, 4.78, and 1.10, divisions per minute. Express the half-value thickness and the coefficient of absorption in $\text{cm}^{-1}$. What possibilities exist for the value of the energy? Calculate the atomic and the electronic coefficients of absorption.

*Answer:* $d_{1/2} = 0.95$ cm, $\mu = 0.729\ \text{cm}^{-1}$, $W = 1.28$ Mev or 15.3 Mev, $\mu_a = 2.2 \times 10^{-23}$, and $\mu_e = 2.69 \times 10^{-25}$.

**2.** Prove that a gamma ray cannot give its entire energy to an electron. Demonstrate that "pair production" cannot be accomplished by a gamma ray in free space.

**3.** A photoelectron from a thin lead foil in a Wilson cloud chamber describes a track whose radius of curvature is 10 cm in a magnetic field of 200 maxwells per $\text{cm}^2$. Assuming the electron to be from the "K" shell, what was the energy of the gamma ray?

*Answer:* $W = .357$ Mev.

**4.** A Compton recoil electron in the same direction as the incident photon has a radius of curvature of 15 cm in a magnetic field of 400 maxwells per $\text{cm}^2$. What is the energy of the gamma ray?

*Answer:* $W_e = 1.36$ Mev, $W_\gamma = 1.58$ Mev.

**5.** The radioactive isotope, tellurium 129, decays by internal conversion. What will be the $B\rho$ values for the K, L, and M electron groups?

*Answer:* $B\rho$ (K) 924, (L) 1099, and (M) 1124 gauss cm.

**6.** Gamma rays whose energies are 1.5, 3.0, and 10.0 Mev, all of equal intensity, are passed through 12 cm of lead. Compare the intensities in the emergent beam.

*Answer:* Intensity ratio $I_{1.5}:I_3:I_{10} = 0.66:2.8:0.78$.

**7.** What minimum energy would enable a gamma ray to make carbon 11 from carbon 12 by photodisintegration?

*Answer:* $\Delta m = 0.0202$ mass units or 18.7 Mev.

**8.** What is the de Broglie wave-length of a 10 Mev deuteron? Of a thermal neutron at 27° C.?

*Answer:* $\lambda = 6.39 \times 10^{-13}$ cm and $1.46 \times 10^{-8}$ cm.

## CHAPTER 7

# NEUTRONS

**7.1. Discovery.** In 1930, Bothe and Becker noticed that light elements, particularly boron and beryllium, when bombarded by the alpha rays from polonium seemed to emit what they assumed were very penetrating gamma rays.[1] I. Curie-Joliot [2] and F. Joliot [3] proceeding on the same assumption measured the absorption coefficients of the supposed gamma radiations in lead. For the radiations from beryllium and boron, respectively, linear absorption coefficients of 0.147 and 0.227 $\text{cm}^{-1}$ were observed. They interpreted this as meaning that the gamma radiation from the beryllium had an energy between 15 and 20 Mev and that from boron about 11 Mev. At that time only the Klein-Nishina formula was considered. It was not yet known that such low-valued absorption coefficients were impossible for any substance because of the absorption due to electron pair formation.

It was observed that when carbon, in the form of paraffin sheets, was placed in the path of the supposed gamma radiation, a new radiation seemed to come from the carbon. This latter radiation behaved like proton radiation but it had a very long range, up to 26 cm in air. Assuming these particles were generated in the carbon by a process similar to the Compton effect, it was necessary to postulate that the energy of the incident gamma quanta was of the order of 55 Mev.

J. Chadwick [4] conducted experiments confirming the conclusion that the particles emanating from the carbon were protons. The only way he could justify their presence was to assume that the radiation from the beryllium or boron was not gamma radiation but rather consisted of energetic neutral particles. These neutral particles were assumed to have arisen from nuclear disintegration induced by the alpha particles and because of their lack of electric charge they could penetrate matter with little absorption. He called the particles "neutrons."

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[1] W. Bothe and H. Becker, *Zeits. f. Phys.*, 66, 5–6, 289 (1930).

[2] I. Curie-Joliot, *Comptes Rendus*, 193, 1412 (1931)..

[3] F. Joliot, *Comptes Rendus*, 193, 1415 (1931).

[4] J. Chadwick, *Nature*, 129, 312 (1932).

A source of neutrons of this type that is now widely used consists of a mixture of radon with beryllium powder or filings. The alpha particles from the radon have an energy of 5.3 Mev. The equation representing the reaction is then

$$ {}_2\mathrm{He}^4\ (5.3\ \mathrm{Mev}) + {}_4\mathrm{Be}^9 \rightarrow {}_6\mathrm{C}^{12} + {}_0\eta^1\ (Q + 5.3\ \mathrm{Mev}) \qquad \textbf{(7.1)} $$

It is apparent that the mass disappearing in the reaction is 0.00600 mass units. This corresponds to a $Q$ value of 5.6 Mev so that the total energy to be carried off in each disintegration is 10.9 Mev. To satisfy the conservation of momentum the neutrons must carry the greater share of the energy. These particles are termed "fast" neutrons.

Subsequent experiments have shown that neutrons may be given off when almost any element is bombarded with high energy particles, such as protons, deuterons, or neutrons. Being neutral in charge, they are the disintegration particles that can most easily escape through the nuclear barrier, provided enough energy exists for their formation.

To produce very high energy neutrons, deuterons of several million electron volts are allowed to fall on a lithium target. This reaction for, say, 10 Mev deuterons may be represented by the following equation,

$$ {}_1\mathrm{H}^2\ (10\ \mathrm{Mev}) + {}_3\mathrm{Li}^7 \rightarrow {}_4\mathrm{Be}^8 + {}_0\eta^1 + (Q + 10\ \mathrm{Mev}) \qquad \textbf{(7.2)} $$

The mass decrease to be accounted for is 0.01632 mass units which represents an energy of 15.2 Mev. The neutrons which proceed in the same direction as the incident deuterons may thus have an energy almost the sum of that of the deuteron plus the reaction energy or 25 Mev.

Another possibility in this same bombardment is that the beryllium 8 nucleus splits into two alpha particles. This seems to occur with about a 50% probability. In this case the mass loss is much greater, being 0.026254 mass units. The alpha particles share almost equally in the energy and they are found to have a range up to 7.8 cm in air corresponding to an energy of 8.7 Mev.

**7.2. The Mass of the Neutron.** Since the neutron carries no net electric charge it cannot be deflected in either a magnetic or electric field. Hence the conventional methods cannot be applied to determine its mass. Only indirect methods may be employed to this end. The masses of the deuteron and the proton may be independently determined in a mass spectrograph to be, namely, 2.014174 and 1.007582. The threshold energy for photoelectric disintegration appears to be close to 2.18 million electron volts. This is equivalent to .002335 mass units. Hence the energy equation in terms of mass becomes:

$$\underset{2.014174}{{}_1\mathrm{H}^2} + \underset{0.002335}{h\nu} \rightarrow \underset{1.007582}{{}_1\mathrm{H}^1} + \underset{\text{mass of neutron (1.00893)}}{{}_0\eta^1} \tag{7.3}$$

The masses involved in this reaction have recently been revised, so that the final mass of the neutron proposed by Hughes[4a] is 1.008937 ± 0.0000075 mass units. Another indirect method has been used which involves the measurement of the energies of the recoiling component particles produced in a known disintegration initiated by a slow neutron. This can be done by having the disintegrations occur in the molecules of the gas within a cloud chamber in a known magnetic field. These measurements can hardly be made with an accuracy sufficient to establish the mass with the certainty obtained in the photodisintegration experiment. Figure 7.1

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[4a] D. J. Hughes, *Phys. Rev.*, **70**, 219 (1946); see also J. Mattauch, *Phys. Rev.*, **57**, 1155 (1940).

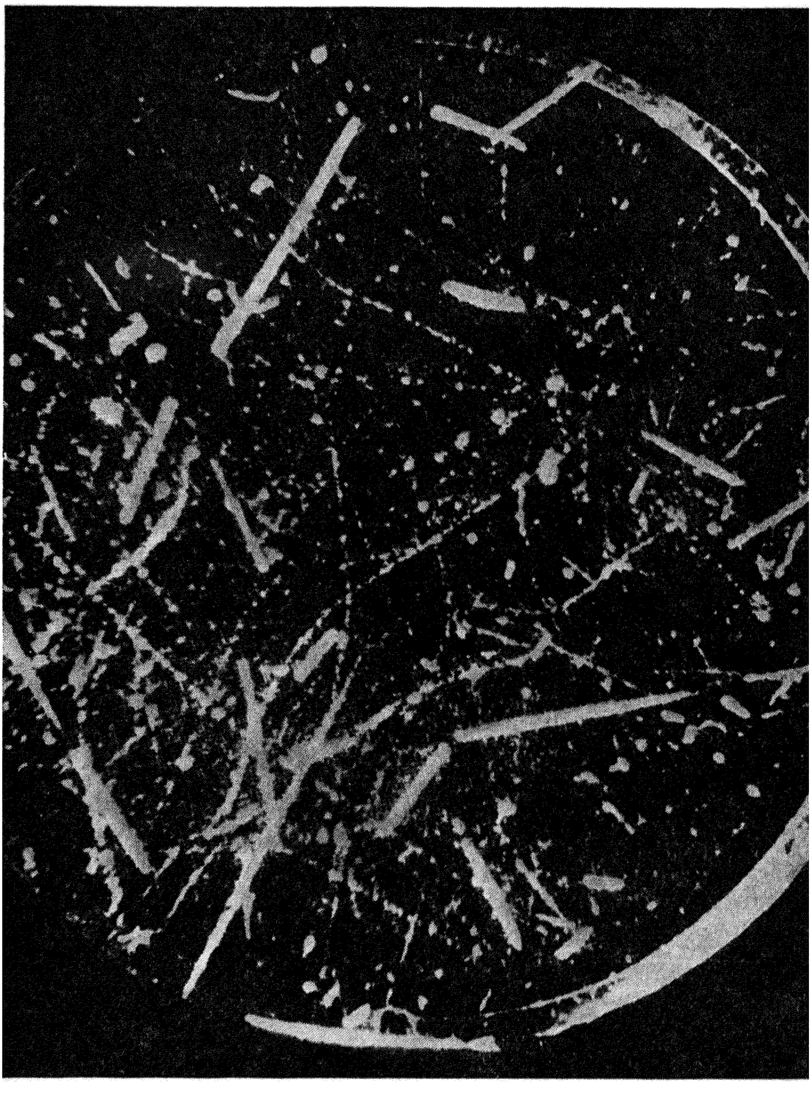

FIG. 7.1. Recoil protons in Wilson cloud chamber produced by neutron bombardment.

shows the dense paths of the recoil protons originating in the gas of a cloud chamber exposed to neutron radiation.

**7.3. The Absorption of Neutrons and Their Range in Matter.** The uncharged nature of the neutron makes it behave very differently in its transit through matter than do such charged particles as electrons, protons, deuterons, or alpha particles. Charged particles can exert electric or magnetic forces capable of ionizing the atoms through which they pass and capable of interacting with the positively charged atomic nuclei. The neutron, however, can experience a force only when it comes within extremely close range of a nucleus. The interaction with the nucleus may be regarded as a collision, which may be either elastic or inelastic.

*a. Elastic Collision.* In an elastic collision the ordinary conservation laws apply. A portion of the energy of the striking neutron is transferred to the struck nucleus. If the target nucleus is extremely heavy, such as lead, then the energy loss by the striking neutron is very small. Light atoms, on the other hand, will at each collision reduce materially the energy of a high-speed neutron. Thus a centimeter of a light material such as water or paraffin will more effectively reduce the intensity of a beam of energetic neutrons than the same thickness of lead. As the energy of the neutron diminishes, it approaches an energy of $\frac{3}{2}kT$ corresponding to that of a particle in thermal equilibrium with its surroundings, where $k$ is the Boltzmann gas constant per particle, $1.37 \times 10^{-16}$ ergs per degree C., and $T$ is the temperature on the absolute scale. It is then often termed a "thermal" neutron or a "C" neutron. At a temperature of 300° K. this energy amounts to about 0.038 electron volts.

For elastic collision in the case of the neutrons from (Ra + Be), Dunning observed the variation in the cross section for atoms of various atomic weights.[5] The results are summarized in Figure 7.2.

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[5] J. Dunning, G. Pegram, G. Fink, and D. Mitchell, *Phys. Rev.*, 48, 265 (1935).

The cross sections are found to increase with atomic weight roughly in the same manner as the geometrical cross section of a sphere whose volume increases proportionally with the number of particles. A beam of fast neutrons was found to be reduced in intensity to half-value by a thickness of about 5 cm of water. For lead a similar reduction in intensity was accomplished by an absorber having 50 gms. per cm$^2$.

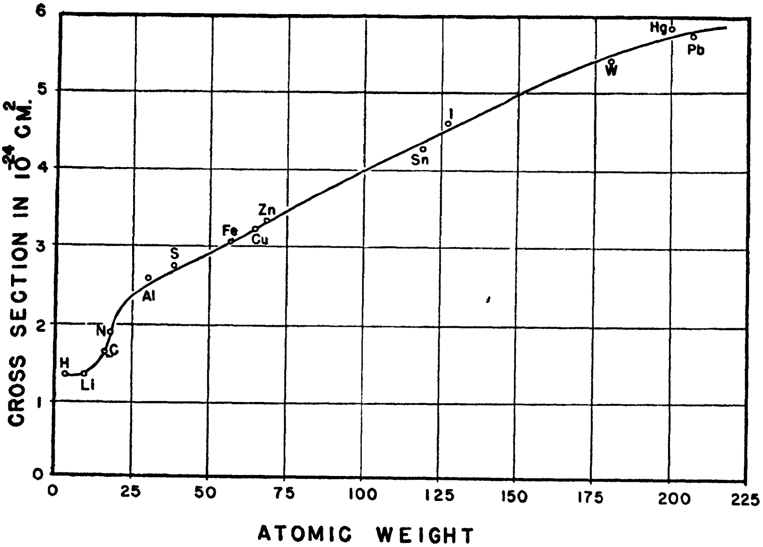

Fig. 7.2. The variation in cross section for the elastic collision of 10 Mev neutrons with various nuclei.

By placing a source such as (Ra + Be) at the center of a sphere of paraffin and increasing the thickness progressively, an optimum radius will be found for which a maximum yield of slow neutrons exists outside the sphere. Using a lithium-lined detecting chamber, Dunning found an intensity variation as shown in Figure 7.3. A maximum neutron intensity exists for a thickness of paraffin of about 10 cm. This phenomenon can readily be explained by assuming that fast neutrons are being converted into slow neutrons by the paraffin and if this conversion gives rise to more slow neutrons than are lost by absorption then the emergent intensity will be augmented. For a thickness greater than 10 cm the absorption predominates and the intensity decreases. A detector for fast neutrons, however, will show a decreasing activity continuously as the thickness increases.

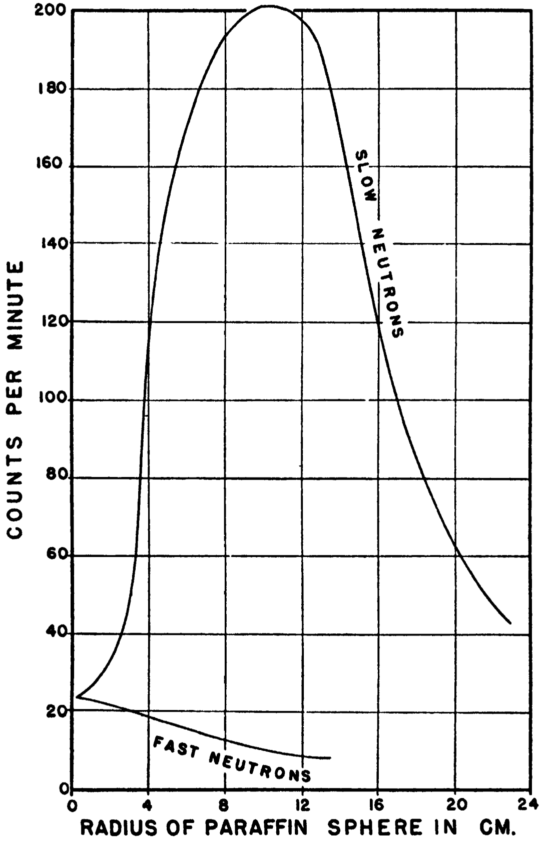

FIG. 7.3. The neutron yield at a fixed distance from a neutron source as influenced by the thickness of intervening paraffin.

*b. Inelastic Collision—Neutron Capture.* The impinging neutron will occasionally enter the struck nucleus and unite with the other particles thereby forming a new isotope of the bombarded element. If as a result the nucleus is left in an excited state, any excess energy may be carried off by the emission of radiation. The new isotope will consequently have a mass one unit greater than that of the target nucleus. This process is termed neutron "capture." The newly formed isotope may have an atomic weight not existing for that element in nature. If this is the case, then this newly created nucleus is bound to be radioactive, that is, it will, by the emission of radiation, convert to a stable nucleus.

A rather exhaustive survey of this neutron capture reaction for the available elements of the periodic table was made by Fermi and his associates at Rome.[6] He used the neutrons from a strong (Ra + Be) source, whose energy has a value up to 10.9 Mev. The radioactivity persisting in the element after bombardment was taken as an indication of the capture reaction. Some elements developed a strong radioactivity while others were inert after bombardment. The half-lives of the activities induced varied from a few seconds up to several days.

Certain elements which show no delayed radioactivity, do emit gamma rays during the bombardment and show a large coefficient of absorption for neutrons. The product nuclei in this case are probably stable isotopes. Many subsequent investigations have been made relative to this phenomenon.[7] The cross section for capture is found to vary greatly from element to element. In some elements such as cadmium and the rare-earths, the cross section is found to be as large as $4000 \times 10^{-24}$ cm$^2$ whereas for other elements it may be less than $0.1 \times 10^{-24}$ cm$^2$. Some observers have reported a periodicity in the capture cross section with steadily increasing atomic number, something like the similar periodicity in atomic volumes. Results of this nature as found by Kikuchi and Aoki are shown in Figure 7.4.[8] The incident neutrons were derived from the bombardment of heavy water by deuterons.

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[6] E. Fermi, F. Amaldi, O. d'Agostino, F. Rasetti, and E. Segré, *Proc. Roy. Soc.*, 146, 483 (1934).

[7] O. Frisch, H. V. Halban, and J. Koch, *Proc. Dan. Acad.*, 15, 10 (1938); C. Lapointe and F. Rasetti, *Phys. Rev.*, 58, 554 (1940); 58, 869 (1940); R. D. O'Neal and M. Goldhaber, *Phys. Rev.*, 59, 102 (1941).

It was noted that the radioactivities induced in silver, rhodium, indium, and many other elements were greatly enhanced by surrounding them with paraffin or other hydrogenous material. Since the layers of hydrogen slowed the incident fast neutrons, this phenomenon was interpreted as showing that the capture cross section varied inversely with the velocity. However, in many substances there was evidence that a resonance capture occurred. That is, at certain definite energies

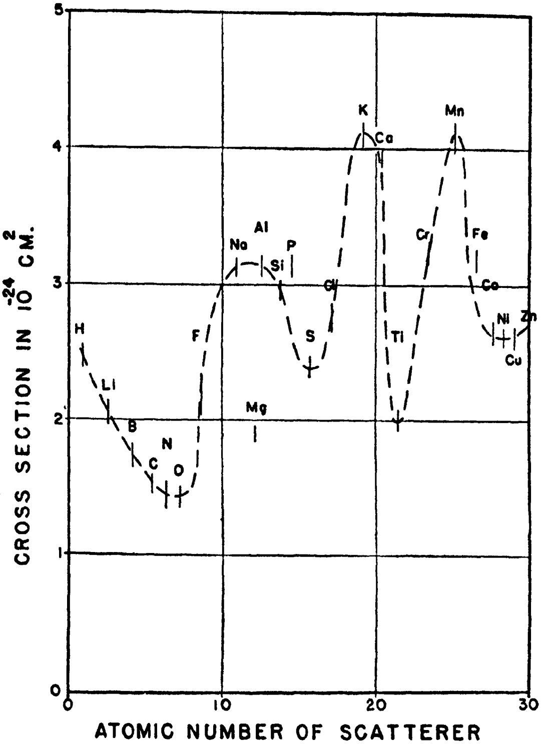

Fig. 7.4. The variation in the capture cross-section neutrons by atoms of varying atomic number.

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[8] S. Kikuchi and H. Aoki, *Phys. Rev.*, 55, 108 (1938).

between the high range and that of thermal neutrons, selective absorption took place accompanied by the appearance of strong radioactivity.

**7.4. Neutron Groups.** Thermal neutrons are strongly absorbed in cadmium and have been designated as "C" neutrons. Their absorption coefficient is about 130 $\text{cm}^{-1}$, or in other words a thickness of cadmium of only 0.053 mm will reduce the intensity to one-half of its original value. Fermi [9] has found for thermal neutrons in paraffin an elastic scattering cross section ($\sigma_e$) for hydrogen of $43 \times 10^{-24}$ $\text{cm}^2$ and a capture cross section $\sigma_c$ of $0.31 \times 10^{-24}$ $\text{cm}^2$. The mean life $\tau$ of the neutron is about $1.7 \times 10^{-4}$ seconds. Next in energy are those neutrons that are strongly absorbed in rhodium, called "D" neutrons. Their absorption coefficient is about 41 $\text{cm}^{-1}$. Other groups of slightly higher energy are the A and I neutrons selectively absorbed in silver and indium, respectively. The absorption coefficient of the A group in silver is about 210 $\text{cm}^{-1}$.

The absorption of neutrons in the uranium isotope of mass 238 is of particular interest in that it leads to the formation of the element plutonium. It was at first reported [10] that a resonance absorption occurred in U 238 at 25*ev*, with a cross section of $1200 \times 10^{-24}$ $\text{cm}^2$. Other later measurements [11] place the absorption at 5*ev* with a cross section of $5000 \times 10^{-24}$ $\text{cm}^2$. Perhaps absorption occurs at several resonance potentials.

The element boron has a large cross section for neutron absorption and it is believed that the absorption coefficient varies strictly inversely with the velocity of the neutrons. It has accordingly been used to determine the energy of the other resonance absorptions. The absorption coefficients of the resonance neutrons and of thermal neutrons are measured in boron. This gives the ratio between the velocities of the neutrons. The energies will vary as the square of the velocities.

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[9] E. Amaldi and E. Fermi, *Phys. Rev.*, **50**, 899 (1936).

[10] L. Meitner, O. Hahn, and F. Strassmann, *Zeits. f. Phys.*, **106**, 249 (1936).

[11] H. L. Anderson, *Phys. Rev.*, **57**, 566 (1940).

Thus if $\mu_r$, $v_r$, and $W_r$ denote the absorption coefficient, the velocity, and the energy, respectively, for the resonance neutrons and $\mu$, $v$, and $W$ the similar quantities for thermal neutrons, then

$$\frac{\mu_r^2}{\mu^2} = \frac{v^2}{v_r^2} = \frac{W}{W_r} = \frac{0.038}{W_r} \tag{7.4}$$

so that

$$w_r = 0.038 \times \left(\frac{\mu}{\mu_r}\right)^2 \text{ (electron volts)} \tag{7.5}$$

Boron trifluoride, being a gas, is admirably suited for use in a discharge tube for detecting neutron radiation. The reaction consists in the absorption of the neutron with the emission of an alpha particle, leaving a lithium residue. It may be represented as ${}_5\text{B}^{10}(n, \alpha){}_3\text{Li}^7$ in which an energy of about 2.5 Mev is released per disintegration. This energy is carried off by the two resulting particles. They produce intense ionization along their path and will initiate a discharge between electrodes if a suitable high potential is applied.

**7.5. Collimation and Production of Neutrons—Monoenergetic Neutrons.** In experimental work with neutrons it is frequently desirable to have a collimated beam, sometimes of a definite energy. A neutron "howitzer" as used by Dunning [12] is shown in Figure 3.18. A source consisting of a mixture of radon and beryllium is located at the bottom of the barrel. It sends neutrons with energies up to 10 Mev outward in all directions. The thickness of the paraffin is sufficient to reduce the number and energy of the neutrons to a negligible quantity in every direction except through the barrel. Layers of cadmium and lead are used to absorb the slow neutrons produced in the paraffin and any gamma rays arising from neutron capture.

The bombardment of heavy hydrogen by deuterons results in a high neutron yield. This reaction may be represented as

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[12] P. Powers, H. Carroll, and J. R. Dunning, *Phys. Rev.*, **56**, 266 (1938).

${}_1H^2(d, n){}_2He^3$, or by the equation

$$ {}_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1 + Q \tag{7.6} $$

The mass discrepancy is 0.003408 mass units corresponding to a $Q$ value of $+3.17$ Mev.

Incident deuterons need have only a very low energy to initiate the reaction. This threshold value for heavy hydrogen may be calculated from the expression for the potential energy as

$$ W = 1.022 \frac{Z}{A^{1/3}} = 1.022 \times \frac{1}{2^{1/3}} = 0.82 \text{ Mev} \tag{7.7} $$

Actually an appreciable yield is obtained for deuterons with an energy as small as 10 Kev.

By bombarding beryllium with high energy deuterons an intense neutron radiation results. By using the deuteron beam in the cyclotron such sources may be equivalent in neutron yield to that from thousands of grams of radium mixed with beryllium. In the forward direction for 10 Mev incident deuterons, the energy of these neutrons is about 14 Mev. This follows from the equation

$$ {}_4Be^9 + {}_1H^2 \rightarrow {}_5B^{10} + {}_0n^1 + Q \tag{7.8} $$

in which 0.00432 mass units disappear, so that $Q$ is 4.022 Mev.

On bombarding lithium with 10 Mev deuterons, a high yield of neutrons with energies up to 25 Mev is obtained, as shown in equation 7.2. To bombard any other substance with these high energy neutrons the specimen is placed close to the lithium, directly opposite to the area exposed to the deuterons. To obtain a collimated beam of neutrons from any of these sources an arrangement of lead and hydrogenous material as shown in Figure 3.19 may be employed.[13] A thickness of 3 cm of lead is sufficient to reduce any direct gamma radiation from the source to a negligible quantity. Other layers of lead absorb the gamma radiation arising from neutron capture in the hydrogen. Well-defined neutron beams may be obtained whose direct intensity is more than one hundred times that existing in the shadow of the outer edge.

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[13] P. Aebersold, *Phys. Rev.*, 56, 714 (1939).

Slow neutrons having a definite energy may be selected in the collimated beam by a technique due to Alvarez.[14] During the bombardment of the beryllium target, neutrons having a rather wide spread in energy are being emitted. Since there is no delayed emission of neutrons, the instant the bombardment ceases the neutrons received at a station a few meters from the target begin to die out. The fast-moving neutrons disappear first and then those with progressively less and less energy. Now by rendering the detecting circuit sensitive only for a few microseconds beginning at a definite interval after the cessation of the bombardment, neutrons with energy not greater than some definite minimum may be observed. To increase the number of slow neutrons the entire beam is passed through a layer of hydrogenous material. Several modifications for pulsing the deuteron output have been introduced. This may be accomplished in the cyclotron by controlling the oscillator, the deflector potential, or the ion source. This technique cannot be extended to obtain monoenergetic neutrons of very high energy. For neutrons of, say, 10 Kev, the effective velocity is $1.4 \times 10^6$ meters per second. The timing of the receiving circuit cannot possibly be controlled with sufficient accuracy to distinguish groups in this range.

By the use of reflecting crystals in connection with the neutron beams from chain-reacting piles, to be described later, intense beams of monoenergetic neutrons may be obtained.

**7.6. Transmutations Produced by Neutrons.** It has been indicated that an inelastic collision of a nucleus with a neutron can take place even if the neutron has a negligible or thermal energy. This is possible because there is no effective nuclear potential barrier to the approach of the uncharged neutron.

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[14] L. Alvarez, *Phys. Rev.*, **54**, 609 (1938); C. P. Baker, R. F. Bacher, and D. Swanson *Phys. Rev.*, **57**, 351, 1076 (1940).

This capture process very often leads to new, unstable, or radioactive isotopes of either the bombarded element or an element standing near it in the periodic table. The type of reaction induced by the bombardment depends largely upon the energy of the incident neutron. The disintegration occurring at impact may consist in the ejection from the compound nucleus of any one of the following: (*a*) gamma ray, (*b*) proton, (*c*) alpha particle, (*d*) two neutrons, (*e*) three particles, and (*f*) fission of the nucleus.

*a. Neutron-Gamma Ray.* In this reaction the product nucleus retains the visiting neutron and any excess energy is carried off by the emission of a gamma ray. The nucleus that is formed is therefore larger in atomic weight by one, than the bombarded nucleus. If this isotope does not normally exist in nature, it is certain to be radioactive. This is a very likely reaction when the energy of the incident ~~energy~~ is low. The abbreviated representation of the reaction is ${}_zA^N(n, \gamma){}_zA^{N+1}$. Any release of energy because of the mass difference between initial and final products, as well as the energy of the incident neutron, will be conveyed away by the gamma ray.

The systematic survey of the elements of the periodic table for this reaction as carried out by Fermi and his associates at Rome has been mentioned.[15] Beginning with oxygen, forty-two different radioactive products were found in the first examination of the elements. This list has been greatly extended by subsequent investigations.

*b. Neutron-Proton.* The uncharged neutron can enter the nucleus with negligible energy. It can also leave without encountering a barrier. For a charged particle such as a proton to escape from the nucleus, however, because of its electrical charge, a potential barrier must be surmounted. In the same way that a certain probability exists for a charged particle to enter the nucleus when its energy is less than the height of the potential barrier, so also may some escaping particles filter out, even though their energy is less than the height of the barrier. As the energy of the escaping particle increases, so also does the probability of its escape. When the energy of the charged particle becomes as great as that of the barrier, the probability of escape is unity and a saturation yield is attained. This process may be regarded as a competing process for straight nuclear capture and becomes relatively more important for incident neutrons of large energy and for elements of low atomic number. The reaction may be represented as ${}_zA^N(n, p)_{z-1}A^N$ or in equation form as

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[15] F. Amaldi, O. d'Agostino, E. Fermi, P. Pontecorvo, F. Rasetti, and E. Segré, *Proc. Roy. Soc.*, 149, 522 (1935).

$$ {}_zA^N + {}_0n^1 \rightarrow {}_{z-1}A^N + {}_1\mathrm{H}^1 + Q \qquad (7.9)$$

The energy $Q$ together with any incident kinetic energy is shared by the resultant particles. The product nuclei are usually emitters of negative electrons and by this emission revert to the original isotope.

*c. Neutron-Alpha Particle.* Certain light elements on being bombarded with energetic neutrons give evidence of disintegrating by emitting alpha particles. This phenomenon has been observed directly in Wilson cloud chambers. A trace of boron trifluoride added to the gas in the chamber will on exposure to a neutron beam occasionally give rise to a disruption showing two heavy tracks. This reaction for the case of boron may be represented as ${}_5\mathrm{B}^{10}(n, \alpha){}_3\mathrm{Li}^7$ or by an equation as

$$ {}_5\mathrm{B}^{10} + {}_0n^1 \rightarrow {}_3\mathrm{Li}^7 + {}_2\mathrm{He}^4 + Q \qquad (7.10)$$

in which a mass loss of 0.00322 mass units occurs, corresponding to a value for $Q$ of 3.0 Mev.

On bombarding lithium 7 in a similar way, each disintegration leads to the formation of two alpha particles together with an electron. A reproduction of these oppositely directed tracks in a photographic emulsion is shown in Figure 4.2*C*. Together the two alpha tracks make almost a continuous straight line.

*d. Neutron-2 Neutrons.* The masses of adjacent isotopes for any one of the heavier elements differ by almost exactly one mass unit, as shown by the Table of Isotopes in Chapter 12. Since their nuclei differ in constitution by one neutron, and the mass of the neutron is 1.00893, then energy must be added to convert the heavier isotope into the lighter plus a neutron. This energy, sufficient to account for the mass 0.00893, and any slight difference as shown by the packing fraction, may be expressed as about 9 ± 2 Mev. Hence if an incident neutron possessing 10 or more Mev enters a nucleus, it may result that two neutrons simultaneously are ejected. In this event the new isotope formed is less in atomic weight by one than the parent nucleus. If the product nucleus does not normally exist in nature, it is almost certain to be a radioactive emitter of positive electrons. This reaction may be represented in general as ${}_zA^N(n,\ 2n){}_zA^{N-1}$ or for a specific isotope such as, say, phosphorus 31, an equation may be written as

$$\underset{30.9839}{{}_{15}\mathrm{P}^{31}} + \underset{1.00893}{{}_0n^1} + W \rightarrow \underset{29.9882}{{}_{15}\mathrm{P}^{30}} + \underset{1.00893}{{}_0n^1} + \underset{1.00893}{{}_0n^1} + \underset{(-0.0132)}{w} \qquad (7.11)$$

In this case the energy $W$ must be greater than $w$ by an amount equivalent to (0.00893 + 0.00430) mass units or 12.3 Mev. The isotope $\mathrm{P}^{30}$ has a half-life of 2.55 minutes and emits positrons with a maximum energy of 3.0 Mev.

This reaction was first observed by Bothe and Gentner.[16] A rather comprehensive survey in which most of the elements of the periodic table were bombarded by 20 Mev neutrons was carried out at the University of Michigan.[17] The neutrons were obtained by the bombardment of lithium with 10 Mev deuterons. From the elements bombarded a total of 115 radioactivities was observed. Of this number about one-third were emitters of negative-electrons and were identified to be the same activities produced by Fermi in neutron capture. The remainder of the newly observed activities were positron emitters of the type here described.

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[16] W. Bothe and W. Gentner, *Naturwiss.*, **25**, 191 (1937).

[17] M. L. Pool, J. M. Cork, and R. Thornton, *Phys. Rev.*, **52**, 239 (1937).

*e. Neutron-3 Particles.* The detachment of each neutron from a nucleus requires 8 to 10 Mev. Thus an incident neutron of energy greater than 20 Mev has in some elements the possibility of inciting a struck nucleus to give off three neutrons or equivalent particles in disintegration. The probability would increase with additional neutron energy. Such neutrons may be derived from lithium bombarded with high energy deuterons, if the neutrons are observed in the direction of the incident deuterons. To establish this process with certainty the product nucleus must be identified. This has been done in the case of sulphur exposed to very high-energy neutrons.[18] The product isotope was identified as phosphorus of mass 30. The reaction may be represented by the symbol ${}_{16}S^{32}(n, 2np){}_{15}P^{30}$ and the equation is

$$ {}_{16}S^{32} + {}_{0}n^{1} + W \rightarrow {}_{15}P^{30} + {}_{0}n^{1} + {}_{0}n^{1} + {}_{1}H^{1} + w \quad (7.12) $$

An alternative reaction would involve the emission of three neutrons together with a positron. The mass discrepancy is $(-0.02296)$ mass units so that $(W - w)$ must represent an energy greater than 20.5 Mev.

*f. Fission by Neutrons.* For the sake of completeness another type of reaction, discussed in more detail later, must be mentioned here. Very heavy nuclei made unstable by the addition of a neutron will sometimes, instead of sending out a small particle, break up into two parts of comparable size. The process is called fission. This has been found to be possible for all elements whose atomic number is 90 or above. The energy required for fission in the case of two of these isotopes, namely, uranium 235 and plutonium 239, need be only that of a low-speed neutron. Other isotopes undergo fission only when the incident neutron carries an amount of energy greater than their threshold values, which in some cases is as high as 1.5 Mev.

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[18] J. M. Cork and W. Middleton, *Phys. Rev.*, 58, 474 (1940).

These heavy elements are all naturally radioactive and in their natural decay would emit over a very long period of time a succession of alpha and beta particles each with considerable energy. In fission, this total amount of energy and more, which is of the order of 190 million electron volts, is released in a single process.

Although fission had been unknowingly carried out first by Fermi [19] and later by Hahn [20] and his associates in Berlin-Dahlem, and in Paris by I. Curie and P. Savitch,[21] the first recognition of the process was the announcement on January 6, 1939, by Hahn and Strassmann.[22]

**7.7. The Scattering of Neutrons.** A knowledge of the laws of force acting between elementary particles is of fundamental importance. Certain facts regarding these forces can be established by observing the scattering of elementary particles by each other. Direct neutron-neutron scattering cannot be

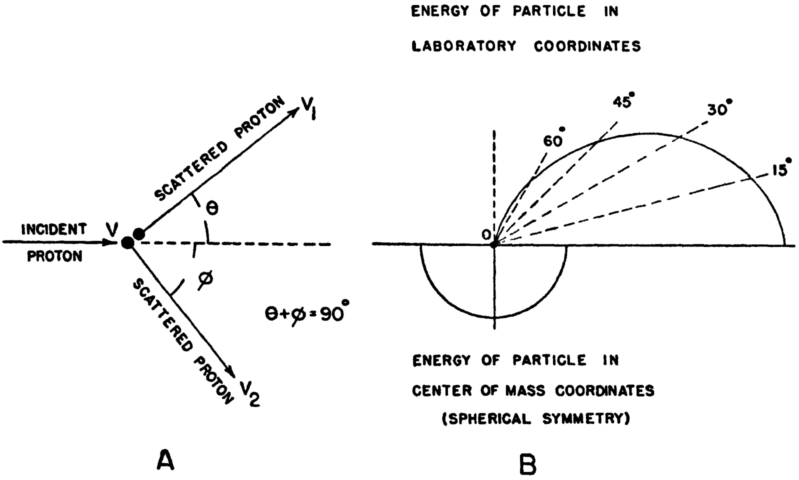
SCATTERED PROTON
$V_1$
θ
INCIDENT PROTON
V
φ
θ+φ=90°
SCATTERED PROTON
$V_2$
ENERGY OF PARTICLE IN LABORATORY COORDINATES
45°
30°
60°
15°
O
ENERGY OF PARTICLE IN CENTER OF MASS COORDINATES (SPHERICAL SYMMETRY)
A
B

FIG. 7.5. The scattering of protons in hydrogen.

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[19] E. Fermi, *Nature*, **133**, 898 (1934).
[20] O. Hahn, L. Meitner, and F. Strassmann, *Naturwiss.*, **26**, 475 (1938).
[21] I. Curie and P. Savitch, *Jour. de Phys.*, **9**, 355 (1938); **206**, 906, 1643 (1938).
[22] O. Hahn and F. Strassmann, *Naturwiss.*, **27**, 11, 89 (1939).

accomplished since neutrons can not be produced and held as a target. The nearest approach is to project a beam of neutrons into hydrogen gas. Observations can be made on either the scattered neutrons or on the recoil protons.

It is common experience that a moving billiard ball on striking head-on another similar ball at rest, will communicate all of its energy and momentum to the struck ball and itself remain at rest at the point of impact. In the same manner, an incident neutron or proton of not too high energy on striking a hydrogen nucleus directly will transfer its entire energy. When a glancing collision occurs, the conservation of momentum and the conservation of energy relate the motions of the two scattered particles as shown in Figure 7.5*A*. Since the masses, whether neutrons or protons, are essentially the same, they need not appear in the equations, so

$$V_1 \cos \theta + V_2 \cos \phi = V \tag{7.13}$$

$$V_1 \sin \theta - V_2 \sin \phi = 0 \tag{7.14}$$

$$V_1^2 + V_2^2 = V^2 \tag{7.15}$$

where $V$, $V_1$, and $V_2$ are the velocities of the incident neutron, the scattered proton, and scattered neutron respectively.

On squaring equations 7.13 and 7.14 and adding, and substituting for $V^2$ its value from equation 7.15, it follows that

$$\tan \theta = \operatorname{cotan} \phi \tag{7.16}$$

Hence $(\theta + \phi)$ must always add to 90°, and the paths of the two particles are at right angles. The energy $W_\theta$ of the particle scattered at an angle $\theta$ is the energy $W$ of the incident particle times $\cos^2 \theta$, or

$$W_\theta = W \cos^2 \theta \tag{7.17}$$

In this case, there can be no back-scattering and $\theta$ cannot exceed 90°. This variation in the energy of the scattered particle at different angles is shown in the upper portion of Figure 7.5*B*. The angles mentioned are measured in the fixed laboratory coordinate system.

It is frequently of interest to consider the scattering as it would appear in a coordinate system whose origin is the center of mass of the two interacting particles. Scattering angles in this system would be double those in the laboratory system. For the direct collision the velocity in the forward direction would be only half that in the fixed system and hence the energy would be only one-quarter as large. This same energy would characterize particles scattered at every other angle. This spherical distribution is shown in the lower part of Figure 7.5*B*.

In the symmetrical, center-of-mass system, the number of particles per unit solid angle ($\sigma$) is the same in every direction. Hence the number of particles ($dn$) scattered between an angle $\theta$ and $\theta + d\theta$ is

$$dn = \sigma \frac{2\pi r^2 \sin \theta \, d\theta}{r^2} \tag{7.18}$$

In the laboratory system the corresponding angle $\theta'$ is equal to $\theta/2$ so

$$dn' = \sigma 2\pi \sin 2\theta' \cdot 2 \, d\theta' = \sigma 8\pi \sin \theta' \cos \theta' \, d\theta' = \mathrm{k} \cos \theta' \, d\theta' \tag{7.19}$$

or the number of scattered particles varies as the cosine of the angle of scattering.

As the energy of the incident neutrons is increased, the scattering process becomes more complicated. A proton and a neutron in close proximity may attract each other because of the exchange of an electron between the two particles, as proposed first by Heisenberg.[23] If the frequency of the exchange is $\omega$, then the energy due to the exchange is $h\omega$, where $h$ is the Planck constant. The variation in the exchange energy with distance corresponds to an attractive force, decreasing rapidly with increasing distance. Such forces are called "exchange" forces.

Calculations have been made of the scattering to be expected for very high energy neutrons on the basis of these more complicated interactions.[24] An asymmetry consisting of an increase of as much as 60% in the number of particles scattered in the forward direction was predicted. Preliminary experiments [25] with neutrons up to 14 Mev failed to reveal any sensible deviation from classical symmetrical scattering.

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[23] W. Heisenberg, *Zeits. f. Phys.*, **80**, 587 (1933).

In the center-of-mass system, the intensity of the scattered particles $I_\theta$ at the angle $\theta$ is calculated to be of the form:

$$I_\theta = c(1 - 0.18 \cos \theta + 0.45 \cos^2 \theta) \qquad \textbf{(7.20)}$$

It should follow from this that the ratio of the intensity at 180° ($I_\pi$) to the intensity at 90° ($I_{\pi/2}$) is 1.63:1. Some other theoretical developments have indicated [26] that this ratio might be as large as 5:1. Experimentally, Amaldi and associates [27] have found for this ratio, values lying between 0.52 and 0.71. It is clear that certain anomalies are still unresolved in this field.

The total cross section for the scattering of 14 Mev neutrons was calculated as $0.66 \times 10^{-24}$ cm$^2$. This quantity has been measured [28] for neutrons up to 25 Mev in both hydrogen and carbon. At low energies the cross section is greater for hydrogen, whereas at 25 Mev the values are, respectively, 1.30 and $0.40 \times 10^{-24}$ cm$^2$ for carbon and hydrogen.

**7.8. The Magnetic Moment of the Neutron and Anomalous Scattering.** Like all fundamental particles as previously noted, the neutron has a spin and a consequent magnetic moment. It was calculated that because of this magnetic moment the scattering of neutrons from the two kinds of molecular hydrogen known to exist, would be quite different.[29] In orthohydrogen the spins of the two nuclei are in the same sense, while in parahydrogen the spins of the two hydrogen nuclei are opposite. Alvarez and Pitzer found that for 20° K. neutrons, orthohydrogen gave about nineteen times the scattering observed for parahydrogen.[30] The hydrogen was in each case at 20.4° K.

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[24] C. Moller and L. Rosenfeld, *Dansk. Math. Fys. Medd.*, **17**, 8 (1940); W. Rarita and J. Schwinger, *Phys. Rev.*, **59**, 552 (1941).

[25] H. Tatel, *Phys. Rev.*, **61**, 540 (1942).

[26] L. Hulthén, *Phys. Rev.*, **63**, 383 (1943).

[27] E. Amaldi, D. Bocciarelli, B. Ferretti, and G. Trabacchi, *Naturwiss.*, **30**, 582 (1942).

[28] Salant and Ramsay, *Phys. Rev.*, **57**, 1075 (1940); R. Sherr, *Phys. Rev.*, **61**, 734 (1942); F. Champion and C. Powell, *Proc. Roy. Soc.*, **183**, 64 (1944); W. Sleator, *Phys. Rev.*, **69**, 681 (1946).

[29] J. Schwinger and E. Teller, *Phys. Rev.*, **51**, 775 (1937); **52**, 286 (1937).

The scattering of thermal neutrons in iron should be influenced by the state of magnetic saturation existing in the iron, because of the interaction between the magnetic moment of the neutron with that of the atoms in the substance. Calculations have been made of the magnitude of the effect to be expected.[31] It has been found experimentally that a change in transmission of about 8% takes place as the state of magnetization of the iron, changes from zero to 97% saturation.[32]

It has also been predicted that the scattering of neutrons in matter depends upon the temperature of the scatterer.[33] Calculations indicate that an increase in temperature from 0° C. to 750° C. should cause a decrease in the scattered radiation by about 7%.

**7.9. The Reflection of Neutrons.** Two types of reflection have been observed in experiments with the strong neutron beams obtained with piles. Neutrons may be reflected by crystalline materials according to the Bragg law for the de Broglie wave-length characteristic of their energy. They may also be totally reflected by highly polished surfaces of selected materials at angles smaller than their critical angle.

It was observed that thermal neutrons on being filtered through a block of graphite 23 cm thick, behaved quite differently than they did initially.[34] Their absorption in boron indicated that their energy corresponded to that of neutrons at a temperature of only about 18° K. The de Broglie wave-length for this energy is about 7.15 Ångstroms. The longest wave-length regularly reflectible by a graphite crystal is limited by the grating constant to 6.69 Ångstroms. It might therefore be expected that of the initial spread of wave-lengths starting out through the graphite, those higher energy neutrons whose wave-lengths are within the Bragg reflecting limit will be scattered out of the forward-proceeding beam, leaving in the end only those low energy neutrons of longer wave-lengths.

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[30] L. Alvarez and K. Pitzer, *Phys. Rev.*, **55**, 596 (1939); **58**, 1003 (1940).

[31] O. Halpern and T. Holstein, *Phys. Rev.*, **59**, 960 (1941).

[32] F. Block, M. Hamermesh, and H. Staub, *Phys. Rev.*, **64**, 47 (1943).

[33] R. Weinstock, *Phys. Rev.*, **65**, 1 (1944).

[34] H. Anderson, E. Fermi, and L. Marshall, *Phys. Rev.*, **70**, 102 (1946).

With the well-collimated beams of neutrons, spectrometers quite like those used in X-ray spectroscopy have been successfully employed.[35] Crystals of calcite and lithium fluoride are satisfactory. The intense reflected beam is thus an ideal monoenergetic group of particles and may be used for studying resonances or allied problems.

The fact that neutrons are scattered by atoms leads to speculation regarding the index of refraction ($\mu$) of various materials for a neutron beam. Experiments on the form factors obtained by the regular reflection of neutrons from various crystal planes indicated that ($\mu - 1$) was of the order of $10^{-6}$, and that it might be positive in sign for some elements and for other elements negative in sign.

Those elements for which ($\mu - 1$) is negative should exhibit a regular reflection within the critical angle. This is similar to the well-known corresponding phenomenon with X-rays. With mirrors of graphite, aluminum, beryllium, copper, zinc, nickel, and iron, intense regularly reflected beams were observed at glancing angles up to 10 minutes of arc. Manganese appears to behave differently, in that its index of refraction for neutrons is greater than unity.

### 7.10. The Physiological Effect of Neutrons and Dosage.

It is well known that a sufficient dosage of any ionizing radiation will kill living tissue. Since neutral radiations like gamma rays and neutrons give rise to energetic charged particles they may be equally effective in destroying living cells. The use of this radiation in medicine is discussed later.

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[35] E. Fermi and W. Zinn, *Phys. Rev.*, 70, 103 (1946).

The intensity of neutron radiation may be measured by the same technique and instrument, such as the Victoreen meter, used in evaluating the intensity of gamma radiation or X-rays. The indication of the instrument on a scale calibrated in roentgen units, is expressed as the same number of "n" units when neutron radiation is being measured. In biological processes one "n" unit is equivalent in effect to from 2 to 10 "r" units of X-rays depending upon the specimen.

Because of the lethal effect of neutron radiation on tissue, care must be observed by workers exposed to it. The effect of radiation applied successively at short intervals is cumulative. To insure the health of operators subjected to continued exposure of X-rays, a safe tolerance dosage has been recognized. For gamma rays and X-rays 3 "r" units or less per month are regarded as not harmful. For neutrons, whose long-range effect is still not known, a more conservative figure of 0.3 "n" per month is recommended as a maximum exposure.

## QUESTIONS AND PROBLEMS

**1.** A neutron has an energy of 5 electron volts. What is its effective velocity? With what temperature would you associate it?

*Answer:* $3.09 \times 10^6$ cm/sec, 38,600° K.

**2.** Lithium is bombarded by 10 Mev deuterons and neutrons are observed leaving the lithium at right angles to the direction of bombardment. By writing expressions for the conservation of momentum and energy determine the energy of one of the neutrons observed. Calculate the energy and the angle of recoil of the associated beryllium 8 nucleus.

*Answer:* $W_b = \sim 5$ Mev, $\theta = \sim 45°$.

**3.** If the intensity of a beam of neutrons is reduced to half-value by a thickness of 5 cm of water, express the absorption coefficient. Calculate the effective cross section in cm$^2$ for the process, dealing only with the hydrogen.

*Answer:* $\mu = 0.1386$ cm$^{-1}$, $\sigma = 1.5 \times 10^{-24}$ cm$^2$.

**4.** If the intensity of a neutron beam 50 cms from its source is 10 "n" units per minute, what thickness of water would safely shield an operator working 40 hours per week? The operator is 10 meters from the source. What would be the effect of scattering around the wall?

*Answer:* For 0.01 "n" per day, thickness = ~45 cm.

**5.** What is the product formed in the water tanks shielding a cyclotron as a result of neutron absorption? Describe the gamma rays produced by a 5 Mev neutron on absorption in a single step.

*Answer:* $W$ = 7.17 Mev.

**6.** Assuming that 1 out of every $10^5$ alpha particles from radon will produce a disintegration in the surrounding beryllium, how many neutrons are emitted per second from a mixture of 100 millicuries of radon and beryllium?

*Answer:* $3.71 \times 10^4$ neutrons/sec.

## CHAPTER 8

# PROTONS, DEUTERONS, AND SOME OTHER PARTICLES

**8.1. The Proton.** The first measurements made on protons were carried out by W. Wien[1] and later by J. J. Thomson[2] in his investigation of the specific charge of the particles comprising the "canal" rays in a discharge tube. The particles were found to be positively charged and if the charge was assumed to be that of the electron, then the mass was shown to be that of the hydrogen atom or the hydrogen molecule.

The proton is the positive nucleus of a hydrogen atom. It can be produced by ionizing atomic or molecular hydrogen by electron impact. In the Bohr theory of the atom it was assumed that the nuclei of all heavy atoms were made up of combinations of protons and electrons. With the discovery of the neutron as a particle emitted by the nucleus, it became more rational to regard all nuclei as built of protons and neutrons. The number of neutrons that will combine with a definite number of protons is seldom unique. For each such combination a particular isotope of the element results.

Protons were first observed as particles emitted in disintegration, by Rutherford in 1919.[3] Nitrogen gas, on exposure to alpha particles from radium, was found to emit protons in all directions. These particles were identified by the scintillations they produced on a zinc sulphide screen in an apparatus shown in Figure 3.1.

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[1] W. Wien, *Wied. Annal.*, **65**, 440 (1898).
[2] J. J. Thomson, *Phil. Mag.*, **13**, 561 (1907).
[3] E. Rutherford, *Phil. Mag.*, **37**, 537 (1919).

**8.2. Transmutation by Protons.** After the discovery by Rutherford that energetic alpha particles would induce atomic transmutation, numerous attempts were made to accomplish the same end by the controlled acceleration of other particles. As previously mentioned, it might have been expected that such reactions would proceed even in the light elements, only if the incident particles had an energy of several million electron volts. From simple electrostatics the potential due to a charge ($Q$), at a distance ($r$), is $Q/r$ and the work required to transport any charge ($e$) through a potential difference, ($V_2 - V_1$) is $(V_2 - V_1)e$. Hence to bring a charge ($e$) from infinity up to a distance ($r$) from the nuclear charge ($Ze$) beyond which point it will be carried forward by attractive forces, is $Ze^2/r$ ergs. By knowing the potential for one or more elements by alpha particle bombardment it becomes possible to deduce the distance ($r$) as a function of the atomic weight ($A$). This was expressed as

$$r = 1.4 \times 10^{-13} \times \sqrt[3]{A} \text{ cm} \tag{8.1}$$

Hence for a proton able to penetrate the barrier of lithium 7 the energy $W$ would be expected to be

$$W = \frac{Ze^2}{r} = \frac{3 \times (4.8)^2 \times 10^{-20}}{1.4 \times 10^{-13} \times \sqrt[3]{7}} \text{ ergs} = 2.6 \text{ Mev.} \tag{8.2}$$

For any other element the threshold energy is

$$W = 1.25 Z^{2/3} \text{ Mev} \tag{8.3}$$

However, it had been shown from the standpoint of quantum mechanics that a certain probability existed for the penetration of the nuclear barrier by particles with much less energy.[4]

The first successful transmutation induced by energetic protons was accomplished by Cockcroft and Walton in 1931.[5] Protons were accelerated by a potential of only 280 KV and were allowed to impinge on lithium as a target. It was found that alpha particles with a range in air of 8.4 cms were emitted from the lithium during the bombardment. This represents an energy of about 8.5 Mev. An improvement in the accelerating equipment soon allowed the production of protons with an energy of 800 Kev. The yield of disintegrations at this energy was many times that at the lower potential. This reaction can be represented by the equation

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[4] R. W. Gurney and E. Condon, *Nature*, **122**, 439 (1928); G. Gamow, *Zeits. f. Phys.*, **51**, 204 (1928).

[5] J. D. Cockcroft and E. Walton, *Proc. Roy. Soc.*, **129**, 477 (1931); **136**, 619 (1932).

$$ {}_1H^1 + {}_3Li^7 \rightarrow {}_2He^4 + {}_2He^4 + Q\ (17.3\ \text{Mev}) \qquad \textbf{(8.4)} $$

The difference in mass on the two sides of the equation is 0.01859 mass units. This mass deficiency means that an energy of 17.3 Mev was set free by the insignificant amount of energy of the incident proton. Even though the energy set free at each disintegration is one thousand times that of the particle initiating the reaction, the probability of the transmutation is so small that no total gain in the release of energy can be anticipated.

As the energy of the incident proton increases, the number of disintegrations per incident particle increases. For a thin target the yield approaches a limiting value as the incident energy approaches in value the height of the nuclear potential barrier characteristic of the bombarded element.

Had Cockcroft and Walton used a slightly larger voltage and examined their lithium target after bombardment they might have been the first to observe induced radioactivity. The bombarded lithium is now known to be radioactive with a half-life of 43 days. This follows from the fact that in the excited beryllium 8, a competitive disintegration process occurs in which a neutron is ejected. The residual atom is a radioactive isotope of beryllium of mass 7, following the equation

$$ {}_1H^1 + {}_3Li^7 \rightarrow {}_4Be^7 + {}_0n^1 + Q\ (-1.6\ \text{Mev}) \qquad \textbf{(8.5)} $$

Many subsequent studies have been made in which transmutations have been induced in elements by protons. Typical of these is the rather complete investigation carried[6] out at the University of Rochester on elements in the periodic table up to tungsten, whose atomic number is 74. This has been accomplished with a proton beam of 6 Mev. Figure 8.1 shows a typical excitation curve as the energy of the incident particles is varied. A "threshold" energy of about 2.5 Mev is apparent, below which the reaction will not proceed. At about 9 Mev a saturation yield is attained.

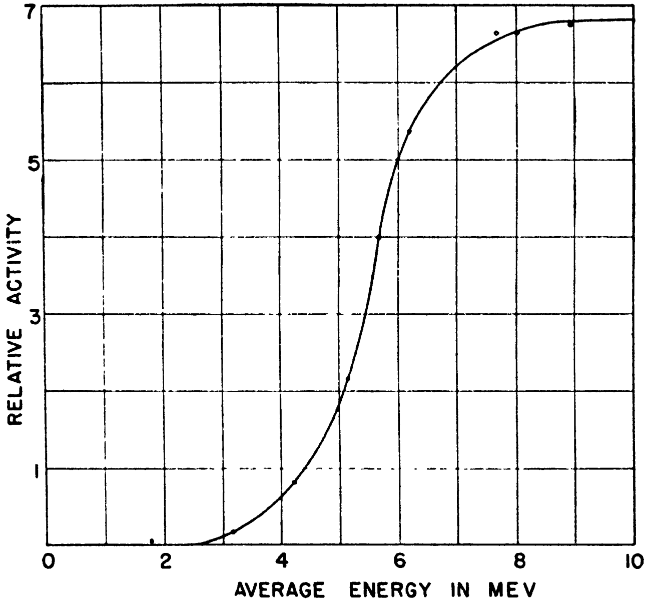

FIG. 8.1. Variation in radioactive yield with the energy of the incident particles.

With the better control of voltage offered by Van de Graaf generators these threshold potentials can be determined with greater accuracy. Typical of such measurements are[7] the following results: 1.86 Mev for the reaction $_3Li^7(p, n)_4Be^7$, and 3.20 Mev for the reaction $_6C^{13}(p, n)_7N^{13}$.

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[6] L. DuBridge, S. Barnes, J. Buck, and C. Strain, *Phys. Rev.*, **53**, 447 (1938); L. DuBridge and J. Marshall, *Phys. Rev.*, **58**, 7 (1940).

[7] R. O. Haxby, W. Shoupp, W. Stephens, and W. Wells, *Phys. Rev.*, **57**, 348 (1940).

**8.3. The Deuteron.** The atomic weight of hydrogen as found by Aston with the mass spectrograph differed slightly from that deduced on the basis of its chemical activity.[8] Birge and Menzel[9] proposed that the difference could be accounted for by assuming the presence of a trace of hydrogen of mass 2, present to the extent of about 1 part in 4500.

The first success in concentrating and identifying the heavy isotope of hydrogen was attained by Urey, Brickwedde, and Murphy in 1932.[10] They evaporated large quantities of liquid hydrogen at its triple point temperature and collected the last fraction. On a spectroscopic examination, they found certain lines not agreeing with those of any molecule reported in the literature. These lines did, however, occur in positions predicted for the spectrum of hydrogen 2. This has been taken as evidence of discovery and the heavy hydrogen isotope was termed deuterium.

The deuterium isotope was positively identified by W. Bleakney by the use of the mass spectrograph.[11] The percentage difference in the atomic weights of the two hydrogen isotopes is so appreciable that their separation by physical methods is a relatively easy matter. It is rendered difficult by the fact that deuterium is normally present only to about 0.018% in ordinary hydrogen. In diffusion, distillation, or electrolysis the lighter component is more active. Consequently, these processes result in a progressive enrichment of the heavier isotope in the residuum. In general in these processes the action proceeds at a rate proportional to the velocity of the particles and hence inversely as the square roots of their masses, since on the average their kinetic energies are the same. Hydrogen consisting of 99.9% deuterium may be readily obtained and has been produced in large quantities in areas of cheap energy. Heavy water is valued at about $0.50 per gram.

[8] F. W. Aston, *Isotopes*, Arnold, London (1924).
[9] R. T. Birge and D. Menzel, *Phys. Rev.*, **37**, 1669 (1931).
[10] H. Urey, F. Brickwedde, and G. Murphy, *Phys. Rev.*, **39**, 164 (1932).
[11] W. Bleakney, *Phys. Rev.*, **39**, 536 (1932).

The ionized deuterium atom has been variously termed, diplon, deuton, and deuteron. The last-mentioned name is now quite generally accepted. Deuterons have been found to be of utmost importance when serving as the charged particles in high energy accelerators.

**8.4. Transmutation by Deuterons.** The deuteron proved at once to be an effective projectile for producing nuclear disintegration. It might have been expected that because of the high energy of the nuclear barriers in all but the very light elements, that transmutations could not be induced by deuterons with energies less than several million electron volts. This was found not to be the case. Two factors contribute to the explanation of this result. As mentioned previously, by wave-mechanics a certain probability exists that the approaching charged particle will filter through the nuclear barrier even though the energy of the barrier is much greater than that of the particle.

A second possibility to explain an induced nuclear reaction by a low energy deuteron was proposed by Oppenheimer and Phillips.[12] It was considered that the deuteron in approaching close to a nucleus in the target might break up into a neutron and a proton provided its kinetic energy was greater than its own binding energy. The neutron, because of its lack of charge, could proceed into the nucleus, but the proton, by virtue of its positive charge, would be repelled or scattered away. The entering neutron could then incite any of the characteristic neutron reactions. Many different types of transmutation can be attributed to the deuteron bombardment, based upon the nature of the particle that escapes from the excited nucleus.

*a. The Deuteron-Neutron Reaction.* One of the reactions first studied was the bombardment of ice, made from heavy water, by deuteron projectiles.[13] For incident deuterons of very low energy a reaction occurred in which neutrons were copiously emitted. At 100 KV it was estimated that one in every $10^6$ incident deuterons produced a disintegration. The reaction can be represented as

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[12] J. R. Oppenheimer and M. Phillips, *Phys. Rev.*, **48**, 500 (1935).

[13] M. L. Oliphant, P. Harteck, and E. Rutherford, *Proc. Roy. Soc.*, **144**, 692 (1934)

$$_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1 + Q\ (3.16\ \text{Mev}) \qquad \textbf{(8.6)}$$

The mass on the left is greater by 0.0034 mass units than that on the right, so that an energy $Q$ (3.16 Mev), in addition to that of the incident particle, will be carried off by the disintegration products.

Another reaction which is now the most common source of neutrons for biological work follows from the bombardment of beryllium with deuterons. The equation for the reaction is

$$_4Be^9 + {}_1H^2 \rightarrow {}_5B^{10} + {}_0n^1 + Q \qquad \textbf{(8.7)}$$

The mass disappearing in the reaction is 0.00432 mass units so that $Q$ is an energy of 4.022 Mev. Neutrons in the forward direction therefore carry an energy slightly less than $Q$, plus the energy of the incident deuteron.

As a source of neutrons of very high energy it has been found practicable to bombard lithium with high energy deuterons. The equation for the reaction is

$$_3Li^7 + {}_1H^2 \rightarrow {}_4Be^8 + {}_0n^1 + Q \qquad \textbf{(8.8)}$$

In this case the loss in mass is 0.01632 mass units which represents a value for $Q$ of 15.18 Mev. In the forward direction of the incident beam, therefore, very high energy neutrons are projected, so that for 10 Mev deuterons the energy of the neutrons may be as great as 25 Mev.

*b. The Deuteron-Proton Reaction.* Other competing processes exist in excited nuclei resulting from the entrance of the deuteron. If the energy is sufficient a proton may be ejected. It might be expected that this would have a low probability compared to that for the escape of a neutron, since the nuclear barrier which made it difficult for the charged particle to enter the nucleus would to the same degree offer resistance to its departure. This is often found not to be the case. For certain elements the relative probability for the two competing processes can be determined.

Figure 8.2 shows the possibility for such a study with bismuth. This element has a single natural isotope of mass 209 and atomic number 83. The deuteron-neutron reaction results in the production of polonium 210, called radium F, while the deuteron-proton process yields bismuth 210, called radium E. Radium E has a half-life of 5.0 days, emitting a beta particle and becoming radium F. Radium F, however, emits only alpha particles and has a half-life of 140 days. By recording the intensity of alpha emission immediately after bombardment, the yield of radium F is established.[14] Then by noting the increase in alpha activity on successive days, as shown in Figure 8.3, the initial yield of radium E can be calculated.

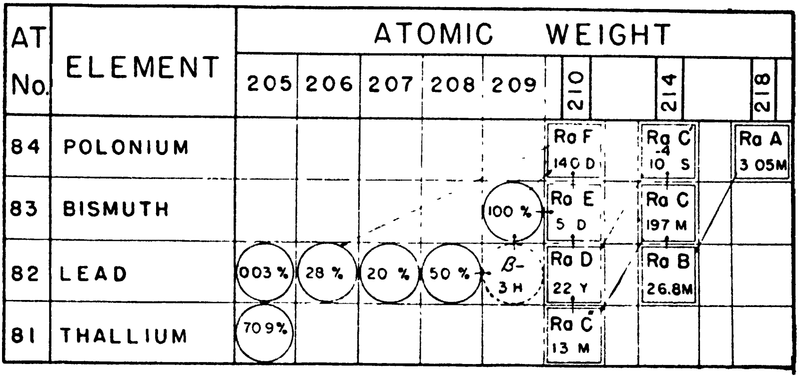

FIG. 8.2. Isotopes, stable and radioactive, for the elements near bismuth.

These relative yields for identical targets bombarded with the same number of deuterons but with varying energy are shown in Figure 8.4. It is clear that at low energies the (*d*, *p*) reaction is much more probable than the (*d*, *n*) process, and at 9 Mev it is still five times as likely to occur. This apparent

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[14] J. M. Cork, J. Halpern, and H. Tatel, *Phys. Rev.*, 57, 371 (1940).

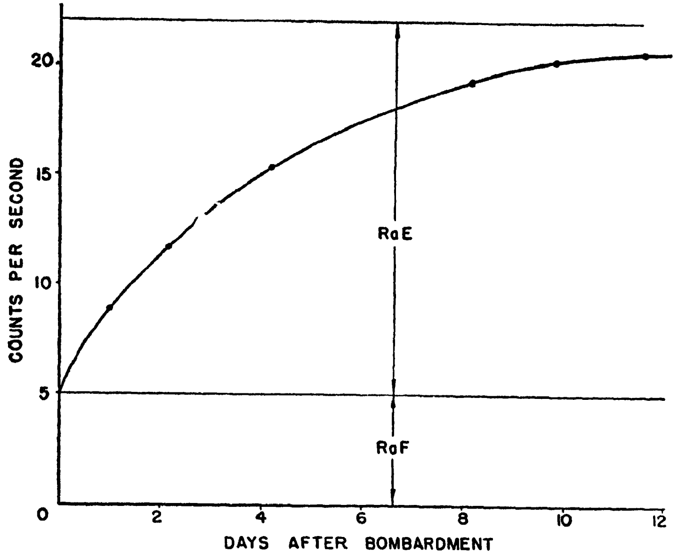

FIG. 8.3. The yield of radium E and radium F from (Bi + $H^2$).

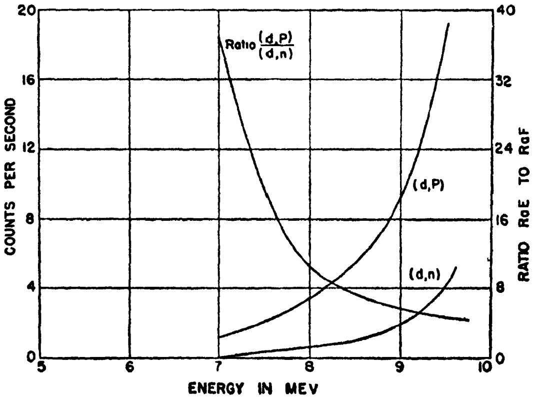

FIG. 8.4. Relative yields of radioactive atoms produced by the escape of a neutron or a proton in the reaction (Bi + $H^2$).

anomaly is not unexpected when the Oppenheimer-Phillips process (page 197) is considered. The greater apparent yield for the (*d*, *p*) process follows because the deuteron decomposes into a neutron and a proton outside of the nucleus. The proton is scattered and therefore does not really come from within the nucleus but only appears to. The neutron proceeds on into the nucleus and incites any of the characteristic neutron reactions, the most common of which is neutron capture.

If the deuteron had entered the nucleus in every case then the ratio of activities might have been expected to be different than that shown in Figure 8.4. Instead the greater yield would have been expected for the (*d*, *n*) reaction. This phenomenon has recently been observed for a bombarding energy up to 14.5 Mev, at which value the O-P process should not be significant. Peculiarly enough the ratio for the (*d*, *p*) to (*d*, *n*) processes seems to remain at a value of about 5, for energies from 9 to 14.5 Mev.

*c. The Deuteron-Alpha Reaction.* There is conclusive evidence that nuclei bombarded by deuterons may, at impact, sometimes emit alpha particles. This fact can be established both by observing in a cloud chamber the particles ejected during the exposure and by studying and identifying the radioactive isotopes resulting from the bombardment. In certain elements it is possible to quantitatively follow this process and compare its probability with that of the reaction in which a neutron escapes from the excited nucleus.

By bombarding pure iron with deuterons, a radioactive isotope of cobalt whose half-life is 18.2 hours, and a radioactive isotope of manganese whose half-life is 21 minutes are formed. Both radioactive elements emit positrons and they are believed to be derived from the same isotope of iron, of mass 54. The former would be produced by a deuteron-neutron reaction and the latter by a deuteron-alpha process as shown in Figure 8.5. This, then, offers an opportunity to observe the relative probability for the two reactions.

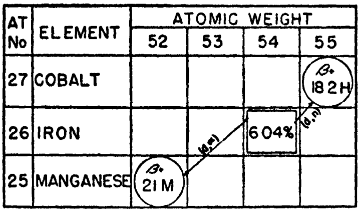

FIG. 8.5. Indicating the possible transitions for ($Fe^{54} + H^2$).

To study the variation in the probability at different excitation energies a stack of thin foils of pure iron is exposed to a beam of deuterons.[15] The cover foil is traversed by deuterons with a maximum energy. Each succeeding underlying foil will transmit practically the same number of deuterons but with a continually decreased energy until the deuterons are completely stopped.

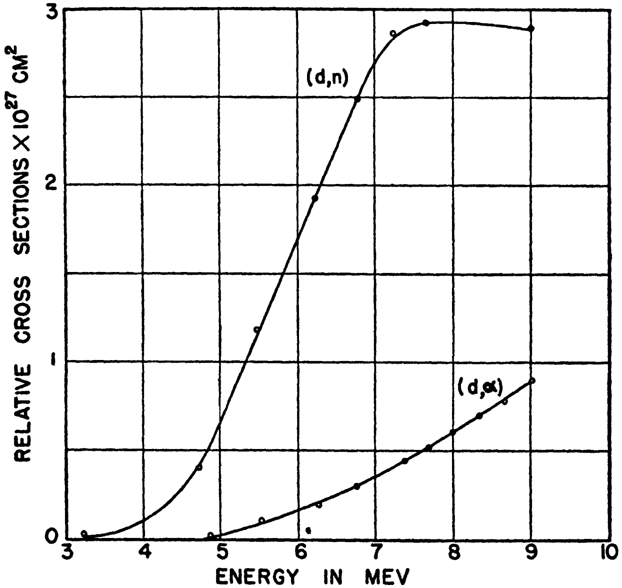

FIG. 8.6. Excitation curves for cobalt and manganese from the reaction iron plus deuterons.

Each foil is then studied individually so as to yield the initial intensities of the 21-minute and 18-hour radioactivities. These quantities for each foil are plotted together with the average energy of the deuterons in that layer, yielding curves as shown in Figure 8.6. The yield from the deuteron-neutron reaction seems to approach a maximum for deuterons of energy about 7.5 Mev and then to show a very slight decrease at higher energies. The yield of the deuteron-alpha reaction increases progressively with increasing deuteron energy. In both cases the deuteron as a whole has entered the nucleus through the potential barrier. The Oppenheimer-Phillips splitting of the deuteron in the external field plays no role, since the reactions considered could not be initiated by a single neutron entering the nucleus.

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[15] J. M. Cork and J. Halpern, *Phys. Rev.*, **57**, 667 (1940).

The decrease in the $(d, n)$ yield at very high potentials might be expected if, with increasing energy, the probability of the competing $(d, \alpha)$ process becomes greater and the total number of excited atoms remains the same. At 9 Mev the emission of a neutron aopears to be about four times as probable as the emission of an alpha particle from this particular isotope.

Except for elements of atomic number greater than lead, no induced radioactive bodies have been formed that exhibit alpha emission after the bombardment ceases.

**8.5. The Production of X-Rays by Deuteron Bombardment.** The possibility of producing X-rays by the bombardment of targets with heavy particles was demonstrated [16] as early as 1913 by Chadwick and by Rutherford and Richardson. Later experiments employing protons [17] at energies up to 1.76 Mev and deuterons with energies up to 10 Mev have been carried out.[18]

If it be assumed that the deuteron collides elastically with the electron then the energy communicated to the electron is classically only $4m/M$ times the energy of the deuteron, where $m$ and $M$ are the masses of electron and deuteron respectively. Hence, deuterons of energy 10 Mev could give to an electron an energy of only 10.9 Kev. This potential would be sufficient to excite the "K" series in elements only up to about atomic number 30. In practice for 10 Mev deuterons "K" radiation has been observed for elements up through atomic number 38. This ability of the heavy particle to communicate more energy to the electron than simple theory would predict has been theoretically explained by Henneberg.[19]

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[16] J. Chadwick, *Phil. Mag.*, **25**, 193 (1913); E. Rutherford and H. Richardson, *Phil. Mag.*, **25**, 722 (1913).

[17] M. Livingston, F. Genevese, and E. Konopinski, *Phys. Rev.*, **51**, 835 (1937).

[18] J. M. Cork, *Phys. Rev.*, **59**, 957 (1941).

**8.6. The Scattering of Protons in Hydrogen.** The nature of the forces acting between fundamental particles can be revealed by observing the scattering of these particles by the same or other nuclei. It is important to note the intensity of the scattering at various angles as the energy of the incident particles is given increasingly large values.

Certain early experiments in which protons were projected against hydrogen gas showed that at an angle of 45° and for incident energies of 600 Kev or higher, the scattering was much greater than would have been expected if only coulomb forces acted between the particles.

Calculations of the scattering to be expected by directing protons against protons (hydrogen) were made by Mott and Massey, utilizing wave-mechanics.[20] In this development they recognized the spin and the identity of the particles in the collision. This formula was soon subjected to experimental verification in several laboratories. White[21] concluded that Mott's formula was valid for energies less than 600 Kev. At higher energies and for scattering angles greater than 20° many more particles were scattered than predicted. Tuve, Hafstad, and Heydenburg counting many more particles found the scattering at different angles as shown in Figure 8.7 for energies 600, 700, 800, and 900 Kev.[22] At 45° the 900 Kev protons were scattered about four times as abundantly as expected.

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[19] W. Henneberg, *Zeits. f. Phys.*, **86**, 592 (1933).

[20] N. Mott and H. Massey, *Theory of Atomic Collisions*, Oxford Press (1933).

[21] M. G. White, *Phys. Rev.*, **39**, 309 (1936).

[22] M. Tuve, N. Heydenburg, and L. Hafstad, *Phys. Rev.*, **49**, 402 (1936); **50**, 806 (1936).

This phenomenon was interpreted as indicating an approach of the interacting particles less than $5 \times 10^{-13}$ cm and the action of other than coulomb forces. The discrepancy was reconciled by a wave-mechanical treatment of the process, by Breit, Condon, and Present.[23] The presence of an attractive nuclear force between the protons at very close contact was indicated. It was predicted that because of the interference between the repulsive coulomb scattering and the attractive effect, at an angle of 45° a minimum scattering should be expected for particles whose energy was about 400 Kev.

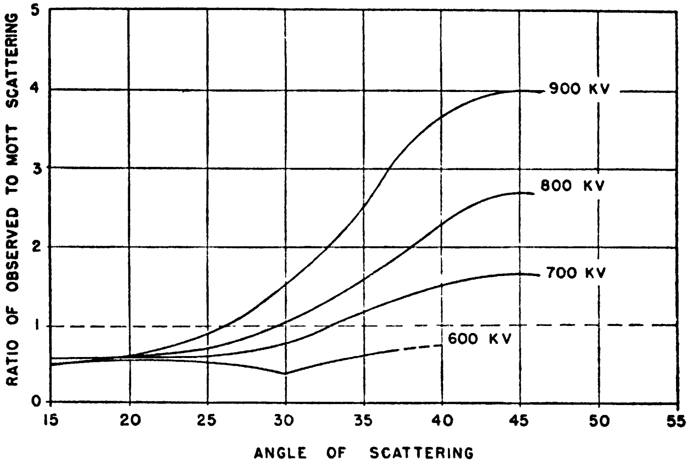

FIG. 8.7. The scattering of protons of various energies by hydrogen (Tuve).

Careful observations have been made to substantiate [24, 25, 26] the existence of this minimum as well as the scattering to be expected for more energetic particles, as predicted by an extension of the theoretical treatment.[27] The data were used to check the possible radius and depth of the potential well characteristic of the proton. The experimental results were not in disagreement with a radius given by $e^2/mc^2$ and a depth of 10.5 Mev, as shown in Figure 8.8. These same dimensions have been assumed in calculations for the scattering of high energy particles and the experimental verification carried out with 8 Mev protons.[28] At an angle of 45° a cross section of $1.7 \times 10^{-25}$ cm$^2$ for the elastic scattering was observed. This agreed closely with the calculated value.

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[23] G. Breit, E. Condon, and R. Present, *Phys. Rev.*, **50**, 825 (1936).

[24] L. Hafstad, N. Heydenburg, and M. Tuve, *Phys. Rev.*, **53**, 239 (1938); **56**, 1078 (1939).

[25] R. Herb, D. Kerst, D. Parkinson, and G. Plain, *Phys. Rev.*, **55**, 998 (1939).

[26] G. L. Ragan, W. R. Kanne, and R. F. Taschek, *Phys. Rev.*, **60**, 628 (1941).

[27] G. Breit, H. Thaxton, and L. Eisenbud, *Phys. Rev.*, **55**, 1018 (1939).

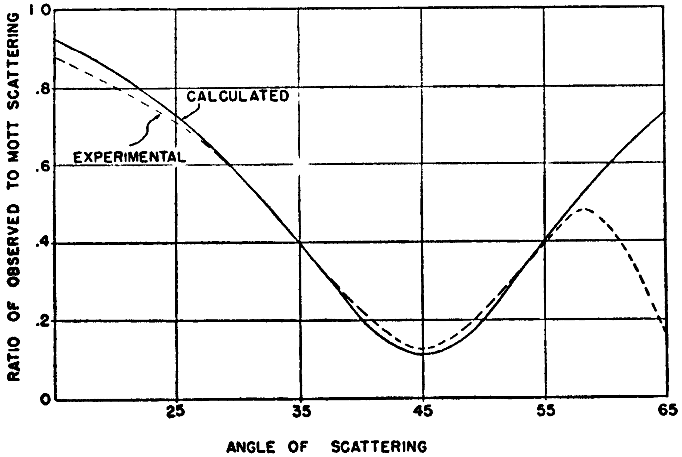

FIG. 8.8. Proton scattering at 45° compared with the calculated distribution.

**8.7. Inelastic Scattering of Protons.** When protons approach very close to other nuclei, in the scattering process, they may transfer some of their energy to the struck nuclei. The proton with its reduced energy is scattered but the bombarded nucleus is left in an excited energy state. This process was first reported by Wilkins in bombarding lithium and magnesium in photographic emulsions.[29] The scattering has been observed directly with a proportional counter, by Dicke and Marshall, using Cr, Al, and Mg as scattering agents.[30] A typical scattering curve showing the number of particles scattered in various energy groups at the fixed angle of 135°, for incident protons of 6.9 Mev on aluminum is presented in Figure 8.9.

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[28] E. Creutz and R. Wilson, *Phys. Rev.*, 61, 388 (1942).

[29] T. R. Wilkins, G. Kuerti, and G. Wrenshall, *Phys. Rev.*, 57, 1082 (1940); 60, 365 (1941); 63, 56 (1943).

[30] R. Dicke and J. Marshall, *Phys. Rev.*, 63, 86 (1943).

The elastically scattered protons have an energy of 6.08 Mev as shown in Figure 8.9*A*, but the inelastic collisions lead to certain groups of particles of lower energy at the same angle, as shown by the definite peaks in Figure 8.9*B*. The energy represented by these peaks, namely 5.26, 4.18, 3.55, and 2.82 Mev, is what remains after the nuclei have taken out their respective characteristic energies, to become excited. These excitation energies, characteristic of aluminum, are accordingly 0.87, 2.03, 2.70, and 3.5 Mev. Similar characteristic excitation energies were observed for many other substances.

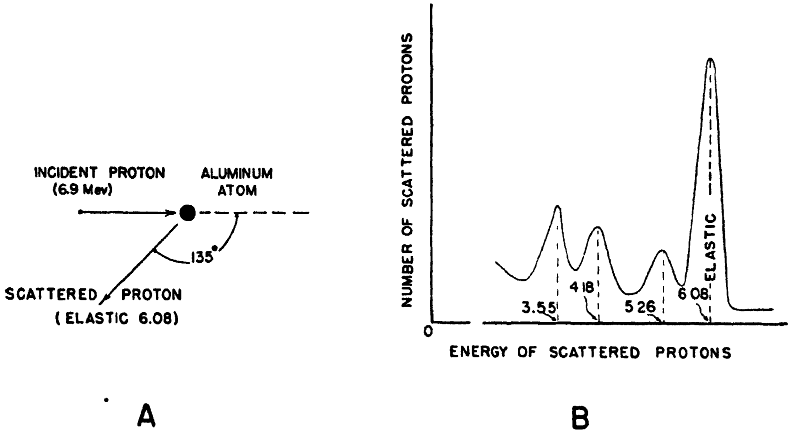

FIG. 8.9. Elastic and inelastic scattering of 6.9 Mev protons from aluminum at an angle of 135° (Dicke and Marshall).

It has been pointed out that charged particles are scattered elastically (Rutherford) mainly in the forward direction, while inelastically scattered particles tend to a symmetrical angular distribution. This indicates that the proton enters the barrier forming a compound nucleus and is then re-emitted with spherical symmetry.

In case the incident particle is a deuteron, it has been shown by Guth that it may be polarized by the nuclear field.[31] In this way the neutron may come close enough to the struck nucleus to transfer energy from the deuteron, producing an excited state, yet the deuteron as a whole will be scattered. This process called "polarization scattering" has been reported by Wiedenbeck for the excitation of indium 115 by 1.7 Mev deuterons.[32]

**8.8. The Range of Protons and Deuterons.** Except for the straggling introduced by statistical fluctuations, the range of a collection of mono-energetic protons in passing through normal air is unique. This variation in range as the energy of the protons is varied is shown graphically in Figure 8.10. A beam of deuterons will behave similarly except that their range

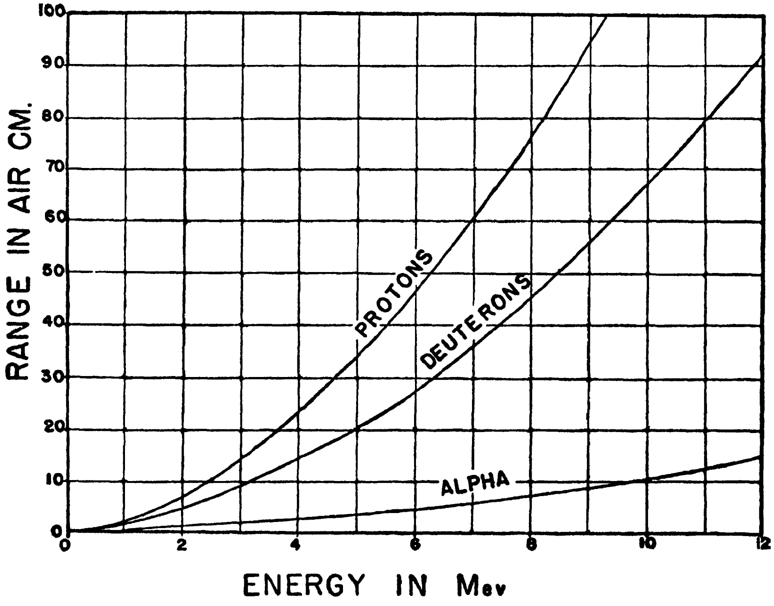

Fig. 8.10. Range-energy relationships for protons, deuterons, and alpha particles.

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[31] E. Guth, *Phys. Rev.*, 68, 280 (1945).
[32] M. L. Wiedenbeck, *Phys. Rev.*, 69, 47 (1946).

for the same energy is much less than that of the proton. The range-energy relationship for deuterons up to 12 Mev is included in Figure 8.10, as well as the range of alpha particles of the same energy.

The range-energy relationship for charged particles is not simple. For low ranges it may be empirically expressed. According to the Geiger rule the range $R$ of a charged particle of a particular kind varies as the cube of the velocity $v$. Since the energy $w$ involves the square of the velocity, then it follows that

$$R \propto v^3 \propto W^{3/2} \tag{8.9}$$

The energy loss per cm of path $dW/dR$ can be found since

$$\frac{dR}{dW} \propto \sqrt{W} \propto v \quad \text{or} \quad \frac{dW}{dR} \propto \frac{1}{v} \tag{8.10}$$

The specific ionization along the path of the singly charged proton or deuteron thus depends upon the reciprocal of the velocity. This indicates that the longer the particle takes to pass an atom the greater is its probability of producing ionization. At the same energy the velocity of a proton is $\sqrt{2}$ times that of the deuteron, and hence it produces only 0.70 times as many ions per cm.

It can be noted from the data shown in Figure 8.10 that over quite a range the following relationship holds, namely, "the range of a proton, whose energy is half that of a deuteron, is half the range of the deuteron."

**8.9. Particles of Mass Three.** Alvarez has shown that an isotope of helium of mass 3 occurs in nature.[33] Its abundance in ordinary helium is estimated at about one particle in $10^8$. In helium derived from oil wells it is about 10 times as abundant, or one in every $10^7$ particles.

Hydrogen of mass 3, sometimes called "tritium," does not exist in nature. It can be produced in such nuclear reactions [34, 35] as

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[33] L. Alvarez and R. Cornog, *Phys. Rev.*, 58, 197 (1940).

$$Be^9(H^2, n)H^3, Be^7 \quad \text{or} \quad {}_5B^{10}(n, H^3)2\,{}_2He^4,$$

or

$${}_7N^{15}(n, H^3){}_6C^{13}$$

It has been estimated that for high energy neutrons on boron or nitrogen the cross section for the production of $H^3$ is about $10^{-26}$ cm². The half-life appears to be about 31 years with the emission of 15 Kev electrons.

**8.10. The Meson and Its Discovery.** In 1935, H. Yukawa presented a theoretical discussion of the short-range forces acting between a neutron and a proton in the nucleus.[36] In accounting for beta disintegration he was led to a prediction of the existence of quanta or particles whose mass should be about one-tenth that of the proton.

In observing the number of droplets per unit length in the photographed track of an ionizing particle in a Wilson cloud chamber it is possible to deduce the number of ion-pairs formed by the particle. From this it is possible to guess at the nature of the particle if its energy is known and not too great. An electron whose energy is 80 Kev will in normal air produce about 200 ion-pairs per centimeter. If its energy is greater than 1.3 Mev its specific ionization is only about 25 ion-pairs per centimeter. At very high energies its velocity approaches a constant and hence its ionization per centimeter remains unchanged. Thus exceedingly energetic particles of the same charge cannot be distinguished by their ionization.

In 1936, Anderson and Neddermyer observed among their many cloud chamber photographs of cosmic radiation, several tracks of particles whose penetration was much greater than it should have been, as indicated by their radii of curvature, if they were electrons.[37] In order to determine more definitely

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[34] R. O'Neal and M. Goldhaber, *Phys. Rev.*, 58, 574 (1940).
[35] R. Cornog and W. Libby, *Phys. Rev.*, 59, 1046 (1941).
[36] H. Yukawa, *Proc. Phys. Math. Soc.* Japan, 17, 48 (1935).
[37] C. D. Anderson and S. Neddermyer, *Phys. Rev.*, 50, 363 (1936).

the nature of such particles it was considered desirable to observe them at the end of their range when they have lost most of their energy. Street and Stevenson, accordingly, arranged a system of four vertical coincidence Geiger tubes with a Wilson cloud chamber placed between the lower two.[38] The circuit was arranged so that heavy particles that penetrated all tubes gave no response, but any particle actuating the first 3 tubes, and not the fourth, set the cloud chamber in action. In this way they obtained a photograph of a negatively charged particle whose mass, as determined by its specific ionization and curvature in a strong magnetic field, was about 200 times the mass of the electron.

Although such tracks are not abundant, several subsequent investigations have [39, 40, 41] shown their existence. The heavy particles appear to be either negatively or positively charged and some reports have been made of similar particles, neutral in character.[42] They have been variously called "yukons," "mesotrons" and "mesons." The last-mentioned name seems now to be preferred.

The intrinsic energy of a particle whose mass is 200 times that of the electron would be about 100 Mev. In the same manner that gamma rays of energy greater than 1.1 Mev can give rise to electron pairs, so radiation of 100 Mev might transform into a meson. Evidence of this nature has been presented by Schein, Klaiber, and Hartzler in their work with the 100 Mev betatron at the General Electric Laboratory.[43] However it now seems that this evidence is not conclusive and that higher energies will be needed.

[38] J. Street and E. Stevenson, *Phys. Rev.*, 52, 1003 (1937).

[39] A. Ruhlig and H. R. Crane, *Phys. Rev.*, 53, 266 (1938).

[40] E. Williams and E. Pickup, *Nature*, 141, 685 (1938).

[41] D. Corson and R. Brode, *Phys. Rev.*, 53, 215 (1938).

[42] G. Groetzinger, P. G. Kruger, and L. Smith, *Phys. Rev.*, 67, 52 (1945).

[43] M. Schein, G. Klaiber, and A. Hartzler, *Phys. Rev.*, 69, 248 (1946).

## QUESTIONS AND PROBLEMS

**1.** A 10 microampere beam of protons at 10 Mev is incident upon a 1 mil (0.001 inch) foil of aluminum for 2 sec. Assume that neutrons are emitted isotropically in the disintegration. A neutron counter 20 cm from the target offers an effective area of 5 sq. cm and indicates that 2000 neutrons are received per second. What is the cross section for the reaction? What is the energy of one of the forward neutrons? What is the energy of a neutron at right angles to the deuteron beam?

*Answer:* $\sigma = 2.09 \times 10^{-28}$ cm$^2$, $W_F = 5.38$ Mev, $W_\perp = 4.8$ Mev.

**2.** The half-life of the silicon isotope formed in problem 1 is 4.9 sec., and it emits positrons of maximum energy 3.64 Mev. How many curies of activity exist in the target at the end of the bombardment? How many curies would exist at the end of a bombardment for one hour?

*Answer:* 13.9 and 50.8 microcuries.

**3.** By bombarding a thick target of phosphorus 31 (30.9839) with 10 Mev deuterons, it is found that 35 microampere hours will produce 1 millicurie of radioactive phosphorus. Assuming a threshold of 3 Mev for the reaction, what is the effective cross section for the process? If the cyclotron beam is 120 microamperes and its operation is valued at $12.00 per hour, what is a fair value for 10 millicuries of radioactive phosphorus?

*Answer:* $\sigma = 4.5 \times 10^{-26}$ cm$^2$, cost, $35.00.

**4.** In problem 3, what is the energy and range in air of the protons emitted at right angles to the deuteron beam? Compute the range in the forward direction, if the target were very thin.

*Answer:* 14.9 Mev.

**5.** A proton whose energy is 0.200 Mev is elastically scattered in hydrogen through an angle of 20°. Describe the behavior of the scattering particle.

*Answer:* $\theta = 70°$, $W = 0.023$ Mev.

**6.** If the average energy per ion-pair is 35 electron volts, how many ions are produced by a 10 Mev proton? What is the average distance traveled in normal air between ionizing impacts? Why should a deuteron of the same energy produce more ions per cm of path?

*Answer:* $N = 2.8 \times 10^5$, $l = 0.0004$ cm.

## CHAPTER 9

# COSMIC RADIATION

**9.1. Historical.** In studying radioactivity by electroscopes it was noticed that with no emitting source present, any charged electroscope would always exhibit a residual rate of discharge. This phenomenon was first studied by Rutherford and Cooke,[1] who found that with all radioactive sources carefully removed, about 10 ions per cm$^3$ per second were continuously formed in a brass vessel filled with air. By completely shielding the electroscope with many layers of iron and lead the production of ions was reduced by about 40%. They therefore concluded that some very penetrating radiation was arriving continuously from outside, which excited a secondary activity in the room. It is now known that the cosmic radiation alone produces at sea level only about 1.8 ion-pairs per cm$^2$ per second in air under standard conditions.

In a balloon flight from Zurich in 1909, A. Gockel[2] noted the rate of discharge of a Wulf electroscope at several different altitudes up to a height of 4500 meters. The rate of discharge seemed to vary erratically from about 60% of normal rate up to three times that value with no general proportionality with altitude. It was generally assumed at that time that the penetrating radiation observed by Rutherford really came from the earth. To test this assumption more carefully, Hess[3] in 1911 made a balloon flight to 1070 meters and later to greater heights with free balloons. He found no diminution, but rather an increase in the penetrating radiation at greater altitudes. He therefore was convinced that the radiation was coming to the earth from interstellar space.

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[1] E. Rutherford and H. L. Cooke, *Phys. Rev.*, **16**, 183 (1903).

[2] A. Gockel, *Phys. Zeits.*, 11, 280 (1910).

[3] V. Hess, *Akad. Wiss. Wien*, **120**, 1575 (1911); **122**, 1053 (1913); W. Kolhorster *Phys. Zeits.*, **14**, 1153 (1913).

In 1913, simultaneous observations were made over a period of several weeks on the penetrating radiation at five different laboratories widely dispersed throughout Europe. No concordance appeared in the observed variations of intensity at the several stations.[4] It was accordingly concluded that the fluctuations, at least, were not of cosmic origin.

**9.2. Nature of Cosmic Rays.** From the fact that cosmic radiation was able to penetrate the entire atmosphere it was generally taken for granted that it consisted solely of energetic gamma rays. This view was supported by an absorption experiment conducted by Millikan in 1928.[5] In noting the absorption of the radiation in water, as the thickness of the water was increased, a complex absorption was observed. On analyzing the data, absorption coefficients of 0.35, 0.08, 0.04, and possibly 0.019 per meter of water were thought to well represent the observed results. By extrapolating the well-established relationship between X-ray wave-length and absorption coefficient, Millikan concluded that these observed coefficients represented the radiation that would be emitted in the process of the building of the four most common elements of the universe, namely, helium, oxygen, silicon, and iron, from hydrogen. The possibility of this interpretation has been shown to be entirely fortuitous.

More recent studies on the variation of the intensity with latitude and with altitude as well as the east-west asymmetry make it seem certain [6, 7] that the primary cosmic radiation consists of high energy protons. In the uppermost layers of the atmosphere the protons may on collision convert into a neutron and one or more mesons (mesotrons). The meson has a mass about 200 times that of the electron and may be either positively or negatively charged. The neutron in turn may revert to a positron and other mesons. Each meson is short-lived and will soon lose its energy by emitting a neutrino or possibly gamma radiation and become an electron. At a depth below the top of the atmosphere these numerous secondary particles as well as secondary gamma radiation may be observed. In general there seem to be two components to the radiation. One is a very penetrating or hard component while another portion is stopped by a few centimeters of lead.

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[4] H. Benndorf, C. Dorno, V. Hess, E. v. Schweidler, and T. Wulf, *Phys. Zeits.*, 14, 1141 (1913).

[5] R. A. Millikan, *Phys. Rev.*, 32, 533 (1928).

[6] W. Heitler and H. Peng, *Proc. Roy. Irish Acad.*, 49, 101 (1943); *Phys. Rev.*, 64, 78 (1943); J. Hamilton and H. Peng, *Proc. Roy. Irish Acad.*, 49, 197 (1944).

[7] O. Wollan, M. Schein, and W. Jesse, *Phys. Rev.*, 59, 930 (1941).

The total atmosphere is equivalent in absorbing power to about 100 cm of lead or 10 meters of water. It must follow, then, that the softer radiation is created continuously at successive depths by conversion of the penetrating radiation. The softer component is undoubtedly electronic in nature while the penetrating radiation may consist of mesons, neutrons, and gamma rays. Evidence for the existence of neutrons has been presented by Korff.[8] By sending a boron-trifluoride counter to various altitudes with free balloons it appears that the intensity of neutrons increases with altitude at a rate faster than the intensity of the general cosmic radiation. The rate of increase is more like that of shower formation, indicating that neutron production is associated with shower phenomena.

Some protons, usually those of lesser energy, appear on a single nuclear collision to produce a disintegration in which a great number of particles are simultaneously ejected. The nature of these particles is not entirely well established. In such a shower formation by a cascade process thousands of secondary electrons and positrons may be derived from a single incident particle.

**9.3. The Earth and Atmosphere as a Magnetic Spectrometer; The East-West Effect.** Although the atmosphere extends, at most, but a few hundred miles upward, the magnetic field is appreciable up to a distance of 10,000 miles. At 400 miles, the magnetic field intensity is about one-eighth that at the surface. It is obvious that a charged particle approaching the earth at its magnetic equator, moving at right angles to the magnetic field, will experience a force at right angles to its velocity and hence may be bent around and away from the earth. This is illustrated by Figure 9.1, in which the observer is looking geographically north along the magnetic axis of the earth. The magnetic field outside the earth is directed into the page and hence any approaching positively charged particles will, by the motor rule, be bent as shown. Since the earth rotates so as to carry an observer toward the east it is apparent that positive particles will be deflected so as to approach any observer more from the west than from the east. Negatively charged particles would of course act oppositely.

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[8] S. A. Korff, *Rev. Mod. Phys.*, 11, 211 (1939); S. A. Korff and B. Hamermesh, *Phys Rev.*, 69, 155 (1946).

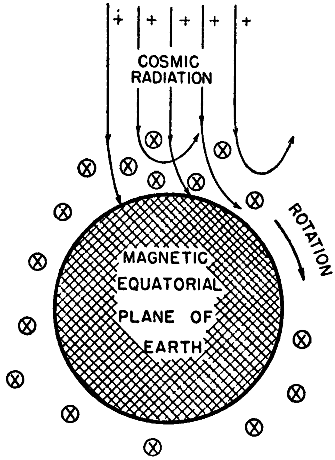

Fig. 9.1. Showing deflection of incident positively charged particles by the magnetic field of the earth, looking north along the magnetic axis.

An analysis of the motion of charged particles approaching the earth in the field of the magnetic dipole was made by Stormer.[9] Figure 9.2 shows the minimum energy that particles may have and yet reach the earth at various latitudes. Curve *A* is for particles arriving along the most favorable direction, curve *B* is for particles arriving at the zenith, and curve *C* is for particles along the most difficult direction. Only those particles can possibly reach sea-level at the magnetic equator in a vertical direction, that have energies greater than a certain minimum energy of about 17 billion electron volts. Lemaitre and Vallarta [10] showed that for energies greater than this minimum, access is possible only for particles within a cone with complicated boundaries.

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[9] C. Stormer, *Terr. Mag. and Atm. Elec.*, 37, 375 (1932).

By using a system of two or more Geiger tubes arranged in a line and connected in a coincidence circuit so as to record an impulse only when the same ionizing particle passes all tubes, an effective cosmic ray telescope results. With an arrangement of this sort the intensities of radiation from the east and from the west at various latitudes and altitudes have been recorded. The results as found by Johnson [11] at Cerro de Pasco, Peru, situated on the magnetic equator at an altitude of 4300 meters, are shown in Table 9.1. The observations were made at angles with the vertical, varying from 15° up to 60°, both in the east and west directions. The asymmetry is expressed in percentages.

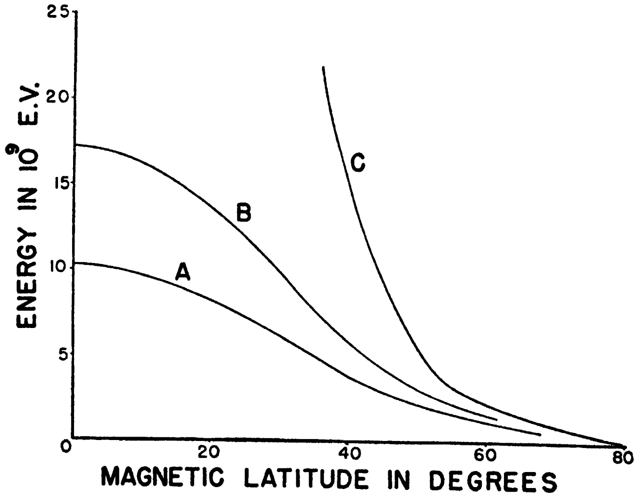

FIG. 9.2. The minimum energy of charged particles able to reach the earth.

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[10] G. Lemaitre, M. Vallarta, and L. Bouckaert, *Phys. Rev.*, **47**, 434 (1935).
[11] T. H. Johnson, *Phys. Rev.*, **48**, 287 (1935); *Rev. Mod. Phys.*, **10**, 194 (1938).

At sea level in the same latitude the results are not appreciably different. This clearly indicates a preponderance of positives in the radiation. It has been shown that at intermediate latitudes the east-west effect does vary with altitude.

TABLE 9.1

| *Zenith Angle* $\theta$ | *Counts West* | *Counts East* | *Asymmetry Percent* |
|---|---|---|---|
| 15 | 59,295 | 55,049 | 8.4 ± 0.4 |
| 30 | 39,601 | 35,418 | 12.5 ± 0.5 |
| 45 | 11,024 | 9,764 | 13.9 ± 0.8 |
| 60 | 6,760 | 6,028 | 17.4 ± 1.5 |

**9.4. The Latitude Effect.** If cosmic radiation consists of charged particles, then a variation in intensity with latitude must be expected. Many particles that would otherwise reach the earth, will be deflected away by the magnetic field. Early measurements by Clay[12] on voyages between Holland and Batavia through the Suez Canal indicated a decrease in the sea-level ionization, due to cosmic radiation, of from 10 to 20% in equatorial latitudes. Other measurements made by Neher[13] on trips from Pasadena (34° N.) to Mollendo (17° S.) failed to observe any deviations in the sea-level ionization greater than the uncertainties in the measurement of from 6 to 7%. Later, more accurate measurements revealed a definite diminution in intensity in equatorial latitudes.[14] A rather complete survey of this effect from magnetic latitudes 59° N. to 45° S., has been made by A. Compton and co-workers.[15] These data averaged for four trips from Vancouver to Auckland are shown in Figure 9.3. It is apparent that the intensity at the equator falls to about 90% of that at the terminal latitudes. For latitudes greater than 40° only a slight change occurs. There is in effect a polar cap including all areas at a latitude greater than about 45°, in which the intensity is essentially constant.

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[12] J. Clay, *Proc. Roy. Acad.*, Amsterdam, **30**, 1115 (1927); *Naturwiss.*, **37**, 687 (1932)

[13] R. A. Millikan and H. V. Neher, *Phys. Rev.*, **43**, 661 (1933).

[14] I. Bowen, R. A. Millikan, and V. Neher, *Phys. Rev.*, **44**, 246 (1933).

[15] A. Compton and R. Turner, *Phys. Rev.*, **52**, 799 (1937).

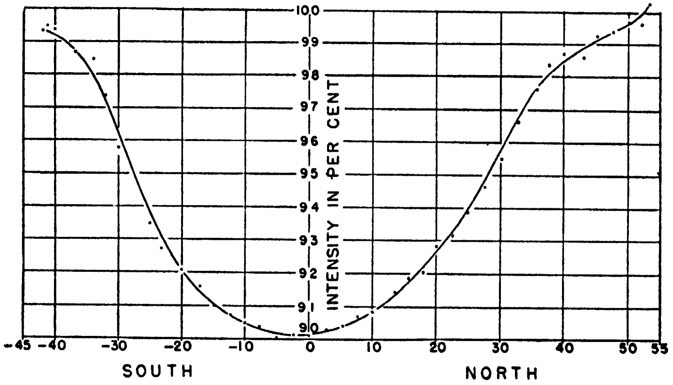

FIG. 9.3. The variation in the intensity of cosmic radiation with magnetic latitude.

**9.5. The Altitude Effect.** The variation in intensity of cosmic radiation with altitude is different at different latitudes. It has been quite fully investigated with small unmanned balloons carrying recording ionization electrometers. A very rugged, lightweight, tilt- and vibration-free instrument has been developed by Neher.[16] It is made entirely of quartz, consisting of a crossarm only 30 $\mu$ thick, supported on a 5 $\mu$ stretched fiber, sputtered with gold so as to be conducting. It is designed so as to give a deflection directly proportional to the potential. The electrometer is charged periodically, at intervals of four minutes, to a constant potential by a charged condenser and the rate of decay recorded on a moving film so that the slope of the discharge curve is a measure of the intensity. The total weight of the instrument, together with the barometric and thermal recorders, was less than four pounds.

[16] R. Millikan and V. Neher, *Phys. Rev.*, 50, 15 (1936).

With groups of ten small balloons in tandem this could be taken to a height where the pressure is only 0.2 meter of water. The entire atmosphere is equivalent to 10 meters of water. is view of the completely assembled instrument with camera A shown in Figure 9.4, together with a record of a 25-minute observation.

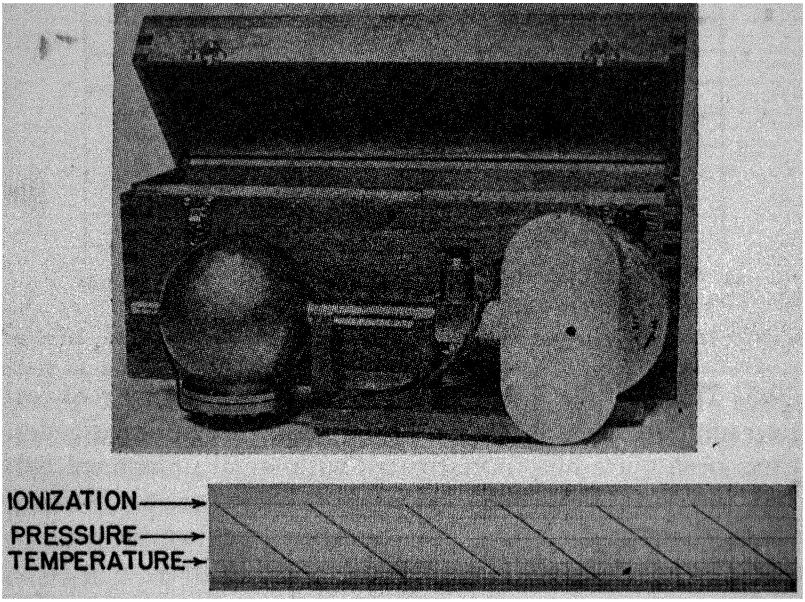

FIG. 9.4. Lightweight recorder for ionization, pressure and temperature (Neher).

The type of curve obtained[17] by plotting the cosmic ray intensity as a function of the altitude expressed in terms of meters of water below the top, is shown in any one of the solid curves in Figure 9.5. Each curve is taken at a different latitude as designated. It is apparent that a maximum occurs at a level about 0.6 meter of water below the top of the atmosphere. The position of the maximum indicates that the exceedingly energetic primary particles react with the outer layer of the attenuated atmosphere producing secondaries. This progressively increases the total number of ionizing particles traveling downward in spite of absorption until an equilibrium state is reached. From the maximum point downward the intensity decreases almost exponentially. This was originally interpreted as indicating a photonic nature for the particles. Their interaction with matter is so complicated, however, that such a conclusion is not justified.

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[17] I. Bowen, R. A. Millikan, and V. Neher, *Phys. Rev.*, 53, 219 (1938).

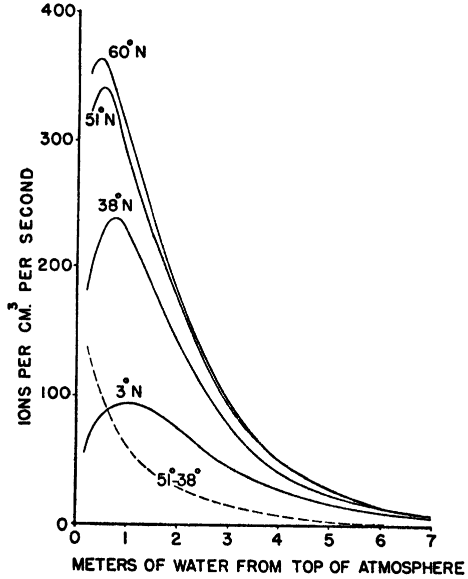

FIG. 9.5. The intensity of cosmic radiation as a function of altitude at four different latitudes.

On forming the difference of any two of the curves in Figure 9.5 it is possible to note the absorption for those particles having an energy lying between the minimum possible energies able to reach the earth at the two respective latitudes. Thus for the curves at latitudes 51° N. and 38° N. the corresponding minimum normal energies are $3.5 \times 10^9$ and $6.7 \times 10^9$

electron volts. The difference curve therefore shows the absorption of particles in this energy band, whose effective value is about 5 billion electron volts.

Millikan and Cameron [18] had studied the absorption of the penetrating radiation in water by lowering an electroscope to various depths below the surface at Muir Lake (alt. 11,800 ft.) and at Arrowhead Lake (alt. 5100 ft.). At the same depth, the ionization in Muir Lake was greater than in Arrowhead by an amount corresponding to 6 feet of water. This is just the water equivalent of the 6700 feet of air between the two elevations.

Regener [19] found traces of radiation at a depth of 220 meters in Lake Constance, and Wilson [20] found at a depth of 1400 meters an intensity 1/20,000 that at the surface. The decrease in intensity with thickness of absorber for the ten billion volt band of particles, as shown by the difference in the curves at 3° N. and 38° N. in Figure 9.5, indicated a coefficient of absorption of 0.54 per meter of water.[21] This means that 1.28 meters of water reduce the intensity to half its initial value. A computation of this value based on the Bethe-Heitler theory has been carried out by many investigators.[22] When only pair production by photons and the energy loss of electrons by radiation is considered, the absorption coefficient predicted is much greater than that experimentally observed.

**9.6. The Longitude Effect.** The many observations of the variation of cosmic ray intensity with latitude, were made on as many different oceanic voyages. These various paths crossed the equator at different longitudes and the apparent equatorial intensities showed a considerable range in values. This variation is illustrated by Table 9.2, showing the intensities observed at sea level for various locations. These data may be interpreted as an indication that the earth's magnetic field even at great heights is not symmetrical but exhibits a definite geographic lopsidedness.

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[18] R. Millikan and G. Cameron, *Phys. Rev.*, **28**, 851 (1926).

[19] E. Regener, *Phys. Zeits.*, **34**, 306 (1933).

[20] V. C. Wilson, *Phys. Rev.*, **53**, 337 (1938).

[21] R. A. Millikan, *Cosmic Rays*, p. 99, Macmillan (1939).

[22] J. Carlson and J. R. Oppenheimer, *Phys. Rev.*, **51**, 220 (1937); H. Bhaba, *Proc. Roy. Soc.*, *A*, **166**, 257 (1938); W. Heitler, *Proc. Roy. Soc.*, *A*, **166**, 529 (1938); R. Serber, *Phys. Rev.*, **54**, 317 (1938).

TABLE 9.2

| *Position* | *Longitude* | *Ions/cm$^3$/sec.* | *Percent Diminution* |
|---|---|---|---|
| Pasadena.. ........ . | 117° W | 1.75 | .. |
| Equator (Singapore) | 105° E | 1.53 | 12 |
| Equator (Center Pac.) | 165° W | 1.57 | 10 |
| Equator (Near S. A.) .. | 90° E | 1.60 | 8 |

**9.7. Cosmic Ray Showers and Bursts.** In the use of ionization chambers to observe cosmic ray intensity, it was noticed that superimposed on the steady ionization current there were occasionally large pulses much beyond any possible random fluctuation. This effect was first reported by G. Hoffmann and F. Lindholm.[23] By arranging Geiger-counter tubes in a horizontal plane and connected so as to actuate a coincidence circuit, Rossi showed that at times a coincidence would occur indicating that several high-speed particles were proceeding downward in almost parallel paths as a group.[24] With the counter at a high altitude, increasing thicknesses of some heavy material such as lead were placed above the tubes. Up to about 2 cms of lead, the number of these coincidence producing showers increased as shown in Figure 9.6. On further increasing the thickness of lead, the number of showers per second fell off rapidly until for about 8 cm an almost saturation value was reached. For thin layers of various materials above the counters, it was found that the shower production per atom varied approximately as the square of the atomic number *Z*.

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[23] G. Hoffmann and F. Lindholm, *Berl. Beitr.*, **20,** 12 (1928).

[24] B. Rossi, *Zeits.f. Phys.*, **68,** 64 (1931); *Phys. Zeits.*, **33,** 304 (1932).

In order to observe more directly the cosmic ray particles, especially designed vertical Wilson cloud chambers were devised.[25] By using a very powerful magnetic field up to 24,000 gauss, Anderson and Neddermeyer [26] were able to estimate the energies of electrons up to several billion electron volts. These observations showed that a typical shower was a complicated phenomenon. Some representative photographs are shown in Figure 9.7. By putting one or more horizontal layers of metal inside the chamber it is frequently observed that a single incident particle will initiate a great number of forward secondary particles in its passage through one of the plates.[27] These secondary particles may in turn initiate additional showers on traversing the next metal plate. This phenomenon is shown in Figure 9.7*A*. The primary shower originates in the upper wall of the chamber and numerous additional secondaries arise in the metallic layer. It is estimated that in total the energy of the numerous particles is greater than 20 billion electron volts. Sometimes these showers seem to originate in the metallic plate and no ionizing incident particle is evident.

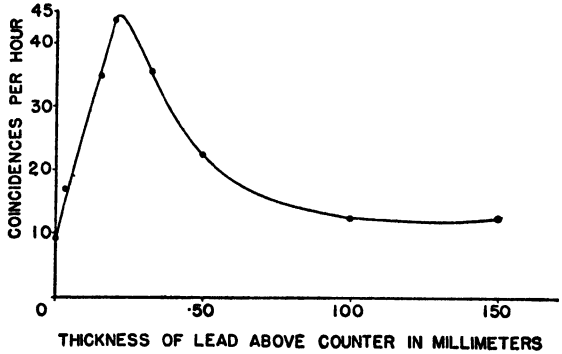

FIG. 9.6. Increase in shower production by interposing lead above coincidence counters (Rossi).

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[25] P. Blackett and G. Occhialini, *Proc. Roy. Soc.*, 139, 699 (1933).
[26] C. Anderson and S. Neddermeyer, *Phys. Rev.*, 45, 295 (1934); 150, 263 (1936).
[27] L. Fussell, *Phys. Rev.*, 51, 1005 (1937).

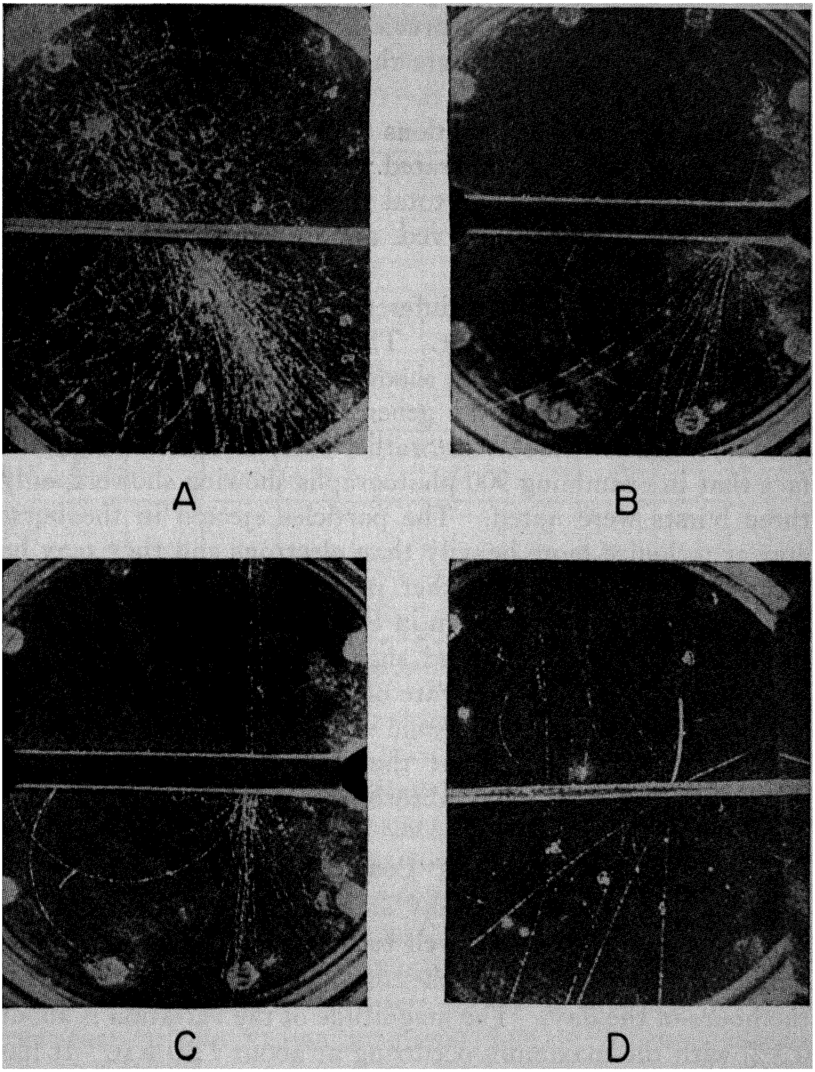

Fig. 9.7. Multiplicative cosmic ray tracks showing showers and burst.

These may accordingly be regarded as induced by neutrons or gamma rays arising from a previous encounter of the primary particle. It therefore appears that many showers take place as a cascade process.

In some recent investigations coincidences have been observed with counters separated by horizontal distances as great as 75 meters.[28] The total energy in some of the most striking showers yet observed approaches a value of $10^{17}$ electron volts.

Occasionally an entirely different kind of shower [29, 30] is observed in the cloud chamber. This is in the nature of an explosion in that the particles shoot out in all directions, rather than being confined to the general direction of the incident primary. Such "bursts" are rather rare, as evidenced by the fact that in examining 900 photographs showing showers, only three bursts were noted. The particles ejected in the burst appear to ionize more heavily than electrons and they may be protons or mesons with either positive or negative charges. Such a phenomenon is shown in Figure 9.7*D*.

The number of bursts and showers increases substantially at higher altitudes. Their rate of increase is more rapid than the rate of increase of the cosmic ray intensity. This has been interpreted as evidence that the showers are intimately related with the more easily absorbed component of the cosmic radiation.

**9.8. Diurnal Variation of Cosmic Radiation.** By noting carefully the ionization at any station, successively, with the lapse of time, it has been well established [31, 32] that a regular variation in the intensity of the cosmic radiation occurs through the hours of the day. The magnitude of the variation is about 0.3% with the maximum occurring at about 1:30 P.M. It has been suggested that this change may be due to a systematic shifting of the earth's magnetic field. A curve showing the averaged variation of the intensity with the hours of the day as observed at a latitude of 20° N. is presented in Figure 9.8.

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[28] P. Auger, R. Maze, P. Ehrenfest, and A. Fréon, *Jour. de Phys.*, 10, 39 (1939).

[29] L. Janosey, *Proc. Roy. Soc.*, 179, 361 (1942).

[30] W. E. Hazen, *Phys. Rev.*, 64, 257 (1943); 66, 254 (1944).

[31] R. L. Doan, *Phys. Rev.*, 49, 107 (1936).

[32] J. L. Thompson, *Phys. Rev.*, 52, 141 (1937).

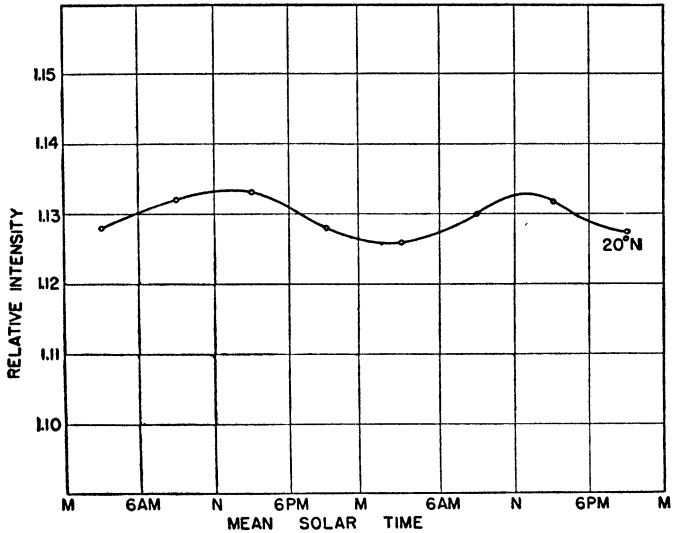

Fig. 9.8. Typical variation of cosmic ray intensity throughout the day (Thompson).

**9.9. The Meson and Its Half-life.** The meson was originally regarded as a particle whose mass was not unique but might lie anywhere from about 40 to more than 200 times that of the electron and whose charge may be either positive or negative. Its introduction was necessary to reconcile the heavy ionization observed along the tracks of certain particles in the cloud chamber with their energy as revealed by their curvature in the known magnetic field. Evidence at the present time seems to favor the assignment of a single definite mass value to the meson of about 200 $m_e$.

The meson is not stable but has a half-life of about 2.3 millionths of a second, probably decaying into an electron and a neutrino. This conclusion on half-life was established by the following experiment. The number of vertical counts in a coincidence circuit was observed, first at a high altitude and then at a low. The difference in the readings might be expected to be due to the absorption in the intervening mass of air. Another reading was now taken at the original high altitude with an additional dense absorber just equivalent in mass to the intervening attenuated air, placed above the counter. It might be expected that this added absorber would reduce the intensity to the same value first observed at the low altitude. Actually this was found by Rossi to be not the case.[33] The condensed absorber produced a much smaller reduction in the reading than did the same mass of attenuated air. This was interpreted as indicating that the mesons in traveling the distance in the air were reduced in intensity by absorption but also by their death or conversion into other types of radiation.

Absorption measurements on mesons have been made at high altitudes and at low.[34] It was found that at an altitude of 9300 meters (22.9 cm Hg), 60% of the mesons have energies greater than 500 Mev, while at sea level only a small fraction have energies in this range.

**9.10. Energy Loss of High-Speed Electrons and Mesons.** When an energetic charged particle passes through matter it loses energy by two processes. These are, namely:

(*a*) Collision with the orbital electrons of the atoms through which it passes. These electrons may be ejected from the atoms or they may be lifted to levels so as to leave the atoms in excited states.

(*b*) Interaction with the strong field surrounding the atomic nucleus, resulting in large accelerations, and consequent radiation losses. These photons radiated may produce high energy secondary electrons.

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[33] B. Rossi and N. Neherson, *Phys. Rev.*, 62, 417 (1942); P. Blackett, *Nature*, 142, 992 (1938).

[34] M. Schein, E. Wollan, and G. Groetzinger, *Phys. Rev.*, 58, 1027 (1940).

The energy loss by collision for an electron, decreases[35] rapidly to a minimum at about 1 Mev and then rises slowly as its energy is steadily increased. For a meson, minimum ionization occurs at about $10^8$ electron volts. For different elements the energy loss per cm of path by collision is proportional to the number of electrons per $\text{cm}^3$.

The radiation loss in different elements increases with the square of the atomic number. In lead, above 10 Mev, and in water above 1 Bev, electrons lose energy mainly by radiation loss. Mesons lose energy mainly by this process at energies greater than 500 Bev.

The energy loss per cm of path in any material, for high energy electrons, by each of the two processes, as computed by Heitler, follows:

(*a*) By radiation

$$\frac{dW}{dx} = \frac{NZ^2}{137}\left(\frac{e^2}{mc^2}\right)^2 W\left(4 \log \frac{183}{Z^{1/3}} + \frac{2}{9}\right)$$

(*b*) By collision

$$\frac{dW}{dx} = \phi_0 \frac{NZ}{\beta^2}\left[\log \frac{(W - \mu)W^2\beta^2}{2\mu I^2 Z^2} + \frac{\mu^2}{W^2}\right]$$

where $\mu$ is the rest energy of the electron $= m_0c^2 = \frac{1}{2}$ Mev.
$W$ is the energy of the electron in terms of $m_0c^2$ or $\mu$.
$I$ is the average ionization energy per pair, usually about 35 ev.
$\phi_0$ is defined as unit cross section $= \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 = 6.57 \times 10^{-25}\ \text{cm}^2$.
$N$ is the number of electrons per $\text{cm}^3$.
$Z$ is the atomic number.

These losses at different energies are shown in Figure 9.9. It should be noted that the energy is plotted logarithmically as abscissae. The ordinate indicates the loss in energy in Mev per cm of lead traversed. This shows that for mesons of energy less than 10 Bev, energy is lost solely by collision.

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[35] W. Heitler, *Quantum Theory of Radiation*, Oxford Press (1936).

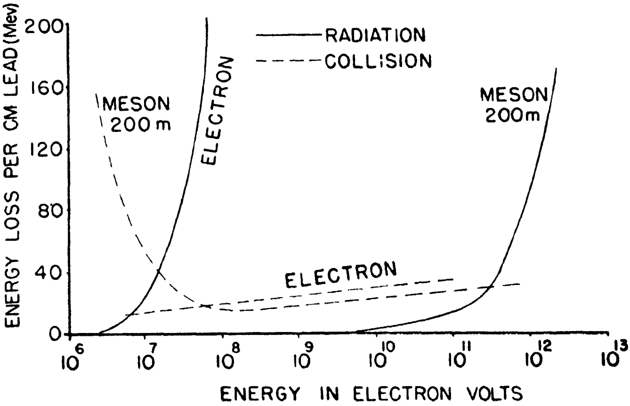

Fig. 9.9. Energy loss per cm of lead for mesons and electrons at high energies.

**9.11. Origin of Cosmic Rays.** With the knowledge that such powerful radiation is coming to us continually from every direction it is only reasonable to speculate regarding its origin. Unfortunately the first very attractive theory of Millikan was groundless when it was shown that the primary radiation did not consist of photons. He had assumed the radiation to be gamma rays resulting from the building of the heavier elements from hydrogen in interstellar space. One might have wondered about the probability in this rarefied space of, say, 54 particles all coming together at a point at the same instant with a willingness to combine and form iron. Such objections were discounted by referring to the largeness of space.

More recently, Millikan, Neher, and Pickering[36] have proposed another theory in which the cosmic particles are thought to spring from the disintegration or annihilation of the heavier atoms in interstellar space. For example, if a silicon atom should erupt into a pair of particles such as mesons or perhaps as large as protons, each particle should have an energy of about 13 billion electron volts. Charged particles of this energy cannot reach the earth vertically at points nearer the equator than a latitude of about 20°. Similarly for oxygen, nitrogen, and carbon the energies are 7.5, 6.6, and 5.5 Bev and the minimum latitudes for vertical reception are 33°, 39°, and 42°, respectively. Helium being the most common disintegrating atom should yield particles of energy 1.88 Bev, which would be able to arrive vertically at the earth only at latitudes greater than 54°. The evidence for supporting this notion is that in flights northward in India from the equator such a plateau in the ionization due to cosmic radiation was found to exist up to a latitude of about 20° N., when a rather sudden increase was noted in the intensity. Similar, not so abrupt, discontinuities have been reported for the nitrogen group and for helium.

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[36] R. Millikan, H. V. Neher, and W. Pickering, *Phys. Rev.*, 63, 234 (1943); 66, 295 (1944); see also S. Kusaka, *Phys. Rev.*, 67, 50 (1945) for an alternate explanation of the observed energy distribution of cosmic radiation with latitude.

There is evidence that the number of atoms per $cm^3$ in interstellar space is somewhere between 1 and $10^{-3}$. Bowen has estimated that hydrogen is the most abundant. For every 100 hydrogen particles there are 10 helium atoms and about one each of the following: carbon, nitrogen, oxygen, and silicon. Even if the latitude observations were incontrovertible, one might wonder what circumstances could possibly incite a heavy atom to such a violent death.

It might well be argued that there is no necessity to consider any improbable process to explain cosmic radiation. Since the radiation appears to consist of protons, and hydrogen is everywhere abundant, all that is necessary is to have the hydrogen ions accelerated in electric fields. The absence of such enormous electric fields would be more surprising than their presence. For example, the electrical capacity of the earth treated as a conducting sphere is only $6.6 \times 10^{-4}$ farads. Thus its potential could be changed a billion volts by the addition of an electrical charge of only $6.6 \times 10^5$ coulombs.

**9.12. Nomograph Relating Momentum, Ionization, and Mass of Energetic Particles.** It is frequently advantageous to relate graphically the various quantities pertaining to the high speed

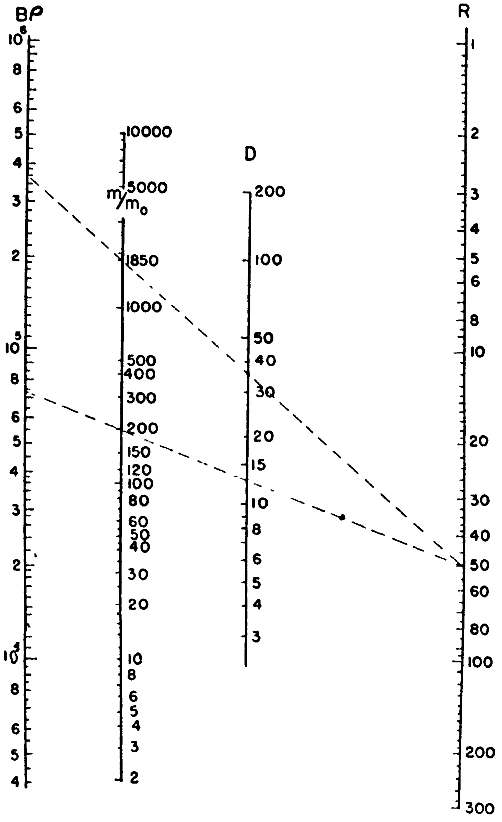

FIG. 9.10. Nomograph relating range $R$, ratio of ions per cm to minimum specific ionization, $D$, ratio of mass $m$ to rest mass $m_0$, and relative momentum $B\rho$.

particles. Such a nomographic relationship as devised by Corson and Brode[37] and extended by D. J. Hughes is shown in Figure 9.10. The quantities represented are the range in normal air, $R$; the ionization expressed as a multiple of the

[37] D. R. Corson and R. Brode, *Phys. Rev.*, 53, 773 (1938).

minimum ionization per cm, $D$; the ratio of the mass $m$ to the rest mass of the electron, $m_0$, and the momentum as expressed by the product of the magnetic induction, $B$, and the radius of the track, $\rho$, as observed in a Wilson cloud chamber. The dotted lines shown represent the characteristics of a proton and of a meson when the range of each is the same. It is thus possible to determine the nature of the particles and their energies uniquely when sufficient information on their ionization and their deflection is available. The nomograph as presented represents the behavior of singly charged particles. For alpha particles it is still suitable provided the $B\rho$, $D$, and $R$ scales be multiplied by the simple factors $\frac{1}{2}$, 4, and $\frac{1}{4}$, respectively.

## QUESTIONS AND PROBLEMS

**1.** A 10-billion-volt electron describes a circular track in a cloud chamber where the uniform flux density is 20,000 gauss. What is the radius of the path? What would be the radius of the track for a proton whose energy is 10,000 Mev?

*Answer:* 1666 cm, 1820 cm.

**2.** At an altitude of 29,000 ft. the pressure is 3.3 meters of water and the temperature is $-60°$ C. Assuming an absorption coefficient of 0.55 per meter of water and a sea-level intensity of 1.9 ions per cm$^3$ per sec., what is the activity at the altitude mentioned? The temperature at sea level is 15° C. and the surface area of a hydrogen-filled balloon is 20 sq. meters. What is its surface area at the high level?

*Answer:* 89 ions/cm$^3$ and 34.9 sq. meters.

**3.** The sensitivity of a certain electrometer is 0.1 volt per scale division. Its capacity is 1 electrostatic unit and the active volume of the chamber is 50 cm$^3$. In what time will the residual cosmic ionization cause a discharge of 10 divisions at sea level and 45° N. latitude?

*Answer:* 21.5 hrs.

**4.** The solar constant at the earth is 0.135 joules per cm$^2$ per sec. Approximately how does this compare with the total energy received per cm$^2$ per sec. due to cosmic radiation, at a latitude of 51° N., obtained by reference to Figure 9.5, assuming 35 electron volts per ion-pair?

*Answer:* Solar/cosmic = $3.9 \times 10^8$.

**5.** The net positive charge of a star is $10^{12}$ coulombs. Its radius is $10^{11}$ cm. Neglecting gravitational effects, how much energy must be expended to bring a proton to the star?

*Answer:* 14.4 ergs or $9 \times 10^6$ Mev.

**6.** Express the intensity of cosmic radiation at sea level, 40° N. latitude, in roentgen units per day.

*Answer:* $7.9 \times 10^{-5}$ $r$/day.

## CHAPTER 10

# NUCLEAR FISSION

**10.1. Historical: The Transuranic Elements.** In his systematic survey of the elements to detect their sensitivity to neutron capture, Fermi [1] observed in uranium several new radioactivities whose half-lives were reported as 10 seconds, 40 seconds, 13 minutes, and 40 minutes. On decay these uranium activities emitted beta particles; therefore the product nuclei must have an atomic number of 93, that is, one greater than uranium, which had been regarded as the heaviest element. The question might well be asked, what becomes of these created atoms of the new element and what are its properties? From the periodic table the element of atomic number 93 should have chemical properties similar to manganese and hence might be separated from the parent element uranium. On making a rapid separation of manganese from the uranium, a beta-active precipitate was obtained. Similarly, on taking from the bombarded uranium, separations of iron, rhodium, or palladium, all were found to be radioactive.[2] The chemistry of these latter elements might have been expected from the vertical columns of the periodic table to be very similar to elements of atomic number 94, 95, and 96. Fermi thus concluded that transuranic elements were being created from the uranium by the action of the slow neutrons.

These experiments with slow neutrons were repeated in other laboratories particularly in Berlin, by O. Hahn, L. Meitner, and F. Strassmann [3] and in Paris by I. Curie-Joliot and L. Savitch.

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[1] E. Fermi, *Nature*, **133**, 898 (1934).

[2] E. Amaldi, O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rassetti, and E. Segré, *Proc. Roy. Soc.*, *A*, **149**, 522 (1935).

[3] O. Hahn, L. Meitner, and F. Strassmann, *Zeits. f. Phys.*, **106**, 249 (1937).

On making more detailed examination of the chemical separations from bombarded uranium, Hahn in 1938 found an activity in a barium precipitate[4] and I. Curie found similarly an activity in a lanthanum separation.[5] Classically the chemistry of none of the transuranic elements should have been similar to either barium or lanthanum. Hahn, at first, reasonably assumed that the radioactivity he was observing was a new form of radium, since the chemistry of radium is much like that of barium. This could be derived from the heavy new elements by the emission of alpha particles. Barium can be separated from radium as shown in Chapter 1. On further tests Hahn became convinced that the activity he was observing was really in barium and not radium. It was somewhat hazardous to depend too positively on the similarity between the properties of the lighter elements and those of the transuranic elements in the same vertical column of the periodic table. It might conceivably be that the properties of the very heavy elements were slightly different.

**10.2. Fission.** On January 6, 1939, Hahn and Strassmann in a continuing report on the radioactivities observed in barium, cerium, and lanthanum stated: ". . . with hesitation because of the strange results, we come to the conclusion our 'radium isotopes' have the properties of barium; as chemists we really ought to say these new substances are barium, lanthanum, and cerium. . . ."[6] They then proceeded to explain the implications of their proposal by showing that among the radioactivities observed was also one with a half-life the same as that of a known isotope of krypton. On combining the barium whose atomic number is 56 with krypton whose atomic number is 36, the number 92 is obtained which is the atomic number of uranium. Hence it might be that instead of the chipping-off of a small fragment from the nucleus as had always been observed in radioactivity heretofore, the nucleus now split up into two fragments of comparable size—a process that has come to be known as "fission." With scientific caution they then stated: "We cannot yet bring ourselves to make this leap in contradiction to all previous lessons of nuclear physics."

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[4] O. Hahn and F. Strassmann, *Naturwiss.*, 26, 755 (1938).

[5] I. Curie and L. Savitch, *Jour. de Phys.*, 9, 355 (1938).

[6] O. Hahn and F. Strassmann, *Naturwiss.*, 27, 11, 89 (1939).

As soon as physicists in other laboratories heard of the proposal that Hahn and Strassmann had envisioned yet had been reluctant to assert, many confirming tests were begun. By the end of February 1939, more than forty published papers on the "fission" of uranium had appeared. The phenomenon became of particular interest because of the tremendous amount of energy released by each atom undergoing fission.

**10.3. Energy of Fission Fragments.** It was soon found that the particles ejected during the fission of uranium were exceedingly energetic. Meitner and Frisch [7] found that by placing the uranium over water, the fission particles were driven out of the uranium and into the water, from which they then could be precipitated.

By covering a surface of bombarded uranium with a stack of thin foils and noting to what foil the radioactivity reached, McMillan was able to form an estimate of the energy per particle.[8]

More direct methods were pursued by Hafstad,[9] Dunning,[10] and Corson and Thornton.[11] The former used an ionization chamber equipped with a linear amplifier and oscillograph so that the deflection observed was proportional to the energy. A copy of such a record is shown in Figure 10.1. The alpha particles from uranium whose energy is 4.1 Mev appear as the dense border at the bottom of the figure. Corson and Thornton placed the uranium on a thin screen inside a cloud chamber and irradiated it with neutrons during the expansion of the chamber. The heavy tracks due to the fission products, to-

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[7] L. Meitner and O. Frisch, *Nature*, **143**, 471 (1939).

[8] E. McMillan, *Phys. Rev.*, **55**, 610 (1939).

[9] R. Roberts, R. Meyer, and L. Hafstad, *Phys. Rev.*, **55**, 416 (1939).

[10] E. Booth, J. R. Dunning, and F. Slack, *Phys. Rev.*, **55**, 981, 1272 (1939).

[11] D. Corson and R. Thornton, *Phys. Rev.*, **55**, 509 (1939).

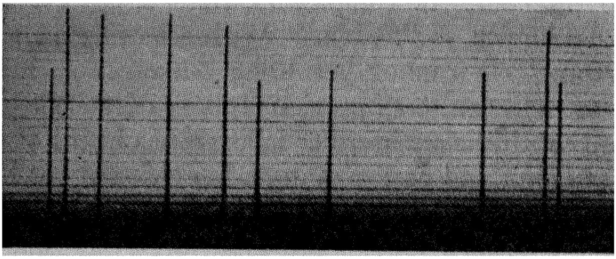

Fig. 10.1. Deflections due to fission particles—alpha particles in dark band at bottom (Dunning).

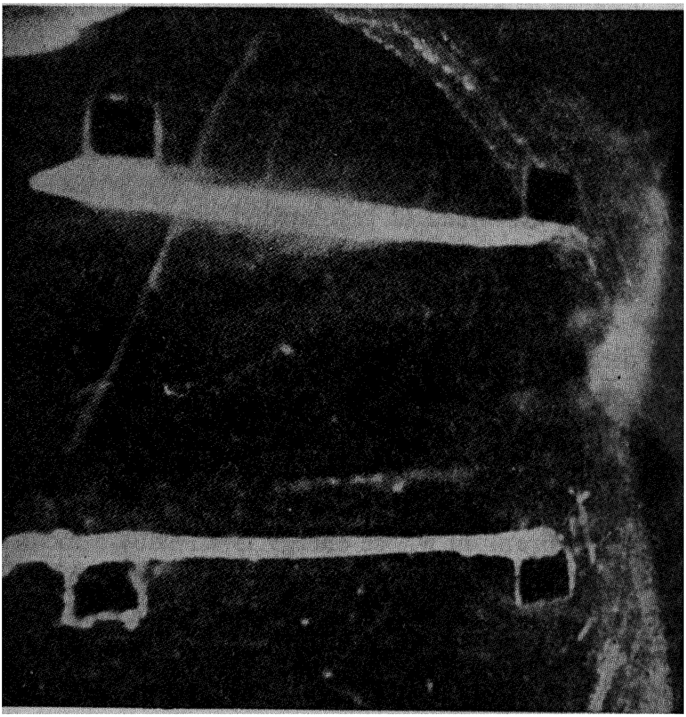

Fig. 10.2. The fission of uranium (Thornton and Corson).

gether with the alpha rays from the uranium, are shown in Figure 10.2.

By observing a large total number of fission particles and noting the number in each energy interval an interesting distribution curve results.[12] As shown in Figure 10.3, two peaks are found to exist, one at 64 Mev and one at 97 Mev. This is about what would be expected from probability theory on, say, the splitting or fission of a raindrop. A division into two equal parts would occur only rarely. The sum of the energies represented by the two peaks is about 161 Mev.

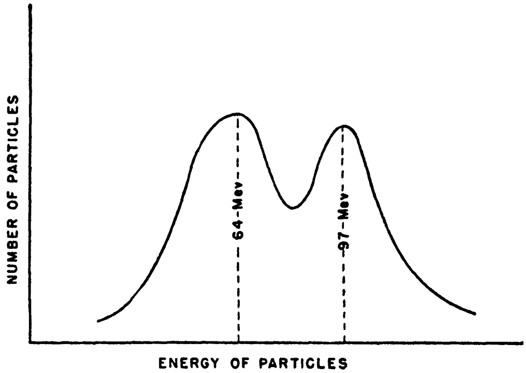

Fig. 10.3. The distribution of energy among the fragments of fission (Kanner and Barschall).

An interesting calorimetric determination of the total average energy per fission was carried out by Henderson.[13] By noting the total number of disintegrations and the total energy developed in a sensitive calorimeter, it was concluded that the energy for fission was about 185 million electron volts. On comparing this with the energy of formation of a molecule in combustion, namely two to five electron volts, its enormous magnitude may be visualized. To represent this energy more familiarly, one pound of uranium 235 consists of $11.6 \times 10^{23}$

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[12] M. H. Kanner and H. Barschall, *Phys. Rev.*, **57**, 372 (1940).
[13] M. Henderson, *Phys. Rev.*, **57**, 774 (1940).

particles which on complete disintegration by fission would yield $34.4 \times 10^{19}$ ergs. This amount of energy is $9.55 \times 10^6$ KWH, or equivalent to the output of a 1000-KW power plant operating continuously for more than a year.

**10.4. Fissionable Isotopes.** The natural isotopes of uranium are 234 (0.006%), 235 (0.710%), and 238 (99.28%).[14] It was shown by Nier in cooperation with Dunning[15] that the isotope of mass 235, comprising only about $\frac{1}{140}$ of the total, undergoes fission by slow (i.e., thermal) neutron capture. For this reaction the remarkably large cross section of $400 \times 10^{-24}$ cm$^2$ was observed. To produce fission in U 238 the neutron must have an energy of about 1.5 Mev. The natural isotope of thorium has a mass of 232, and it was shown by Nishina and associates[16] at Tokyo that it will undergo fission by 1.1 Mev neutrons. A small quantity of protactinium, whose mass number is 231, was examined by the Columbia group[17] and found to split up when the neutron energy was more than about 1.0 Mev. It is quite probable that any element of atomic number 90 or more will succumb to fission under neutron bombardment of the proper energy. Most important is the fission of plutonium whose mass is 239 and atomic number 94.

**10.5. Neutron Production at Fission and the Chain Reaction.** As soon as it was certain that slow neutrons could initiate fission in U 235, then it became of interest to find if any additional slow neutrons result from the process of fission. If so, these slow neutrons could excite other U 235 atoms, which in turn would lead to fission in others, so that the action would proceed with increasing violence as a "chain" reaction if only U 235 atoms were present.

It was found[18] without question that neutrons were set free at fission, the number being from one to three per atom. That this should be the case is not surprising, on considering Figure 10.4. The isotope U 235 by capturing a neutron becomes an atom of mass 236 and atomic number 92. If it should divide into two identical parts these fragments would be palladium isotopes of atomic number 46 and mass 118. They would be highly unstable, since the heaviest natural isotope of palladium has a mass 110. By the emission of either neutrons or beta particles, or both, they would approach stability. They might therefore produce any one of several of the radioactivities as shown in Figure 10.5. In addition to the neutrons given off during bombardment, a delayed neutron emission with a half-life of 12.5 seconds was at first reported. The neutrons generated at fission were noted to be not thermal neutrons but possessing energies up to the order of 1 Mev. On further observation it was found by Snell [19] that about 1% of the neutrons emitted

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[14] A. O. Nier, *Phys. Rev.*, 55, 150 (1939).

[15] A. O. Nier, E. Booth, J. Dunning, and A. V. Grosse, *Phys. Rev.*, 57, 546 (1940).

[16] Y. Nishina, Y. Yasaki, and H. Ezoe, *Nature*, 144, 547 (1939); R. Haxley, W Shoupp, W. Stephens, W. Wells, and M. Goldhaber, *Phys. Rev.*, 57, 1088 (1940).

[17] A. V. Grosse, E. Booth, and J. Dunning, *Phys. Rev.*, 56, 382 (1939).

[18] R. Roberts, L. Hafstad, R. Meyer, and P. Wang, *Phys. Rev.*, 55, 664 (1939).

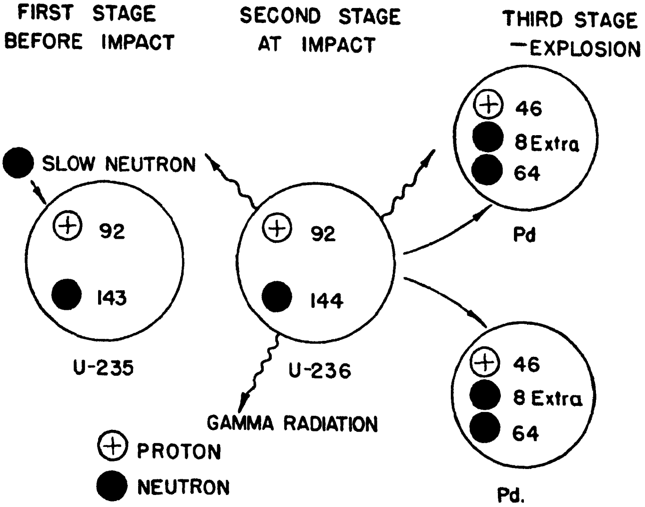

Fig. 10.4. The imaginary fission of U 235 by a thermal neutron into equal palladium isotopes.

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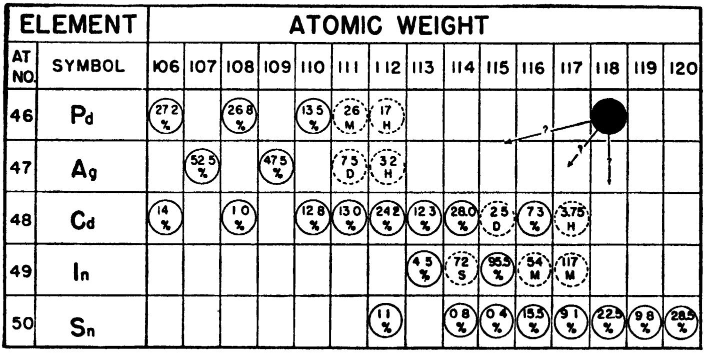
[19] A. Snell, A. Nedzel, and Ibser, *Smyth Report*, Princeton Press (1945).

in fission are delayed by at least 0.01 second and about 0.07% are delayed by as much as a minute. This would be a satisfactory condition for a chain reaction provided the newly formed neutrons were allowed to unite with other atoms of U 235.

In natural uranium this process was forbidden by the presence of a preponderant number of U 238 atoms. A resonance absorption for neutrons in U 238 was reported by Anderson and Fermi[20] at an energy of about 25 electron volts with a capture cross section of $1.2 \times 10^{-24}$ cm$^2$. A theoretical consideration of the fission, by Bohr and Wheeler,[21] concluded the level width for capture was only about 0.003 electron volts for 25-volt neutrons. This capture leads to the radioactivity whose half-life is 23 minutes, which had been identified[22] as the only one of the many neutron-induced activities in uranium really obeying the chemistry of uranium. All the other numerous half-lives were related to elements of lesser atomic number. Other observers had found for the total absorption cross section of neutrons in uranium a value of $23 \times 10^{-24}$ cm$^2$. Meit-



| ELEMENT | | ATOMIC WEIGHT | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AT NO. | SYMBOL | 106 | 107 | 108 | 109 | 110 | 111 | 112 | 113 | 114 | 115 | 116 | 117 | 118 | 119 | 120 |
| 46 | Pd | 27.2 % | | 26.8 % | | 13.5 % | 26 M | 17 H | | | | ? | | ● | | |
| 47 | Ag | | 52.5 % | | 47.5 % | | 7.5 D | 3.2 H | | | | | ? | ? | | |
| 48 | Cd | 1.4 % | | 1.0 % | | 12.8 % | 13.0 % | 24.2 % | 12.3 % | 28.0 % | 2.5 D | 7.3 % | 3.75 H | | | |
| 49 | In | | | | | | | | 4.5 % | 72 S | 95.5 % | 54 M | 117 M | | | |
| 50 | Sn | | | | | | | 1.1 % | | 0.8 % | 0.4 % | 15.5 % | 9.1 % | 22.5 % | 9.8 % | 28.5 % |

FIG. 10.5. The elements near palladium, indicating possible transitions for the two equal fission isotopes shown in Fig. 10.4.

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[20] H. Anderson and E. Fermi, *Phys. Rev.*, **55**, 1106 (1939).

[21] N. Bohr and J. Wheeler, *Phys. Rev.*, **56**, 426 (1939).

[22] L. Meitner, O. Hahn, and F. Strassmann, *Zeits. f. Phys.*, **106**, 249 (1937).

ner, Hahn, and Strassmann had noted for resonance absorption an effective cross section of $1200 \times 10^{-24}$ cm$^2$.

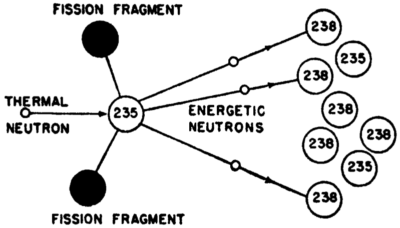

Fig. 10.6. Showing the fission of a U 235 atom and the resonance capture in U 238 of the neutrons produced at fission.

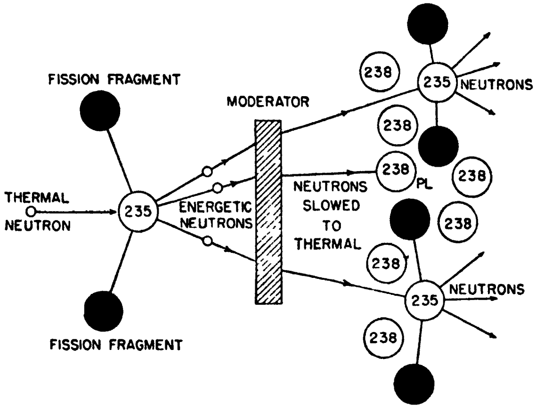

Fig. 10.7. Showing the action of the moderator to slow the created neutrons to the thermal range.

The problem to be solved was, how could the neutrons formed at fission be slowed to thermal neutrons without being captured by U 238 as their energy passed through the resonance value, a process shown in Figure 10.6. Fermi suggested that this absorption might be averted by the judicious use of what has become known as a "moderator." This is an element of rather light atomic weight whose atoms will not accept the neutrons in capture but which will scatter them elastically. Such elements suggesting themselves were deuterium, helium, beryllium, and carbon. The moderating atoms will thus take a portion of the energy of the neutron at each collision, and as a result the original high energy neutrons may be reduced to thermal neutrons. They can now diffuse back into the composite uranium and have a strong probability of inducing fission in other U 235 atoms. In a collision with a carbon nucleus, a neutron will lose about one-sixth of its energy per collision. It was found that a neutron travels about 2.5 cm in graphite between collisions.[23] The geometry of the moderator could be arranged so that on the average about 120 elastic collisions took place, before the particle, now a thermal neutron, returned to the uranium. This behavior is suggested in Figure 10.7, and leads to a successful chain reaction.

**10.6. The Separation of the Uranium Isotopes.** If the spontaneous disintegration of U 235 is prevented by the presence of U 238 it might seem desirable to separate the isotopes, or at least to proceed to a product sufficiently enriched in U 235. The separation of heavy isotopes which differ by only a few mass units is not easy.

Four different methods suggest themselves as possible means to achieve this end. These are the magnetic mass spectrograph, molecular diffusion methods, thermal diffusion towers, and the centrifuge.

*a. Electromagnetic Separator.* In a strong, uniform magnetic field, particles having the same energy but unequal masses will describe circular paths of unequal radii. The radii will be approximately in the same ratio as the square roots of the masses. The particles are given the same energy by being accelerated as ions through a fixed potential difference.

In the mass spectrographs as shown in Chapter 2, the currents are usually less than a microampere. The accelerating voltage source and auxiliary circuits all involve the expenditure of considerable energy. To deposit one pound of U 235, consisting of $11.6 \times 10^{23}$ particles, using ordinary uranium 140 times as many uranium atoms in total must be transported. One ampere corresponds to a transfer of $6.24 \times 10^{18}$ singly charged particles per second. By using a current this large,

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[23] H. D. Smyth, *Atomic Energy Report*, Princeton Press (1945).

$26.1 \times 10^6$ seconds, or 302 days, would be required for the deposition of one pound. Thus for conventional spectrographs utilizing a current of 1 microampere, the prohibitive number of one million instruments operating for 300 days would suffice to yield one pound of U 235.

Factors important in the successful operation of such separators are (*a*) the size and shape of the arc source from which the ions come, (*b*) the accelerating voltage, (*c*) strength and deliberate nonuniformity of the magnetic field, (*d*) pressure of vapor in the ion source and in the chamber, (*e*) the design of the collector, and (*f*) the mutual interaction between particles in the beam and between neighboring beams. By successfully meeting many of these issues at Berkeley in 1942, the output of such separators was increased by an enormous factor.[24] The final practical separators of this type used successfully in large numbers were termed "calutrons."

*b. Separation by Molecular Diffusion.* The average kinetic energy per particle of a gas is dependent only on the absolute temperature. Hence at the same temperature, any two gas particles of masses $m_1$ and $m_2$ having velocities $v_1$ and $v_2$, respectively, will diffuse at a rate proportional to their velocities. Thus

$$\frac{v_1}{v_2} = \sqrt{\frac{m_2}{m_1}}$$

so that for the 235 and 238 isotopes of uranium the velocities are as 1.0064 to 1. Hence in any continued electrolytic, evaporation, or diffusion process the lighter particles will participate more actively. By continually collecting this first product to escape, an enrichment of the lighter isotope will be accomplished.

In attempts at separation by diffusion, the uranium is converted to the heavy, very poisonous gas, uranium hexafluoride. The two molecules $UF_6$ have masses 349 and 352, so that their relative velocities are only 1.0043 to 1.

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[24] H. D. Smyth, *Atomic Energy Report*, Princeton Press (1945).

The unequal rates of diffusion through semipermeable walls was used,[25] soon after the discovery of isotopes, to partially separate the isotopes of neon. Various improvements in technique by Hertz led to an apparatus consisting of as many as 48 separating components of which the first and last stages are shown [26] in Figure 10.8. Starting with the normal gas at the left, a portion relatively enriched in the lighter component diffuses through $T_1$. This is caught by the mercury-vapor pump $P_1$ and circulated through $T_2$ and $T_3$. Again a lighter fraction through $T_3$ is taken by pump $P_2$, while the heavier component returns to the original reservoir. This process is repeated through the many successive stages, resulting in almost complete separation for the lighter gases.

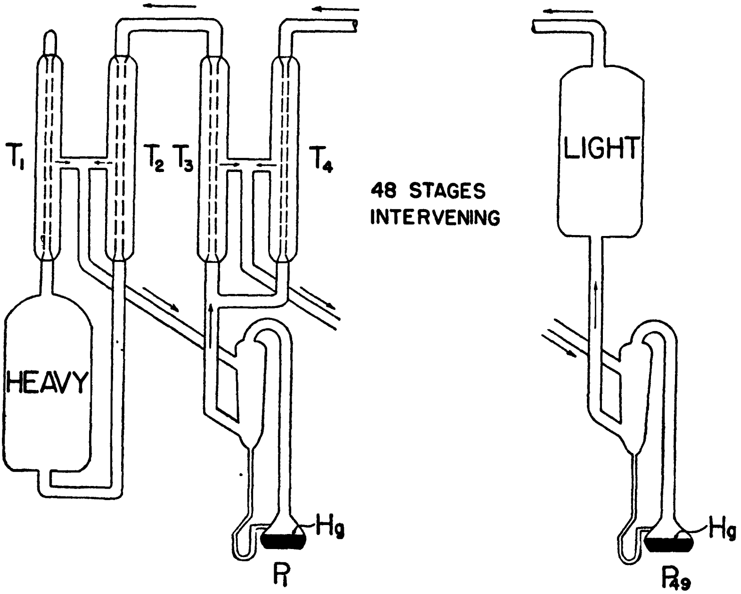

FIG. 10.8. The separation of isotopes by the unequal rates of diffusion through semipermeable walls (Hertz).

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[25] F. Lindemann and F. W. Aston, *Phil. Mag.*, 27, 523 (1919).
[26] H. Harmsen, G. Hertz, and W. Schutze *Zeits. f. Phys.*, 90, 703 (1934); 91 810 (1934).

For the separation of the isotopes of uranium a satisfactory barrier had first to be developed. After this was successfully accomplished more than 4000 successive cycles had to be allowed to obtain the desired enrichment. The scale of operation as carried out at Oak Ridge comprised what has been termed the largest continuous chemico-physical process in the world.

*c. The Thermal Separating Tower.* By allowing the convection of a fluid consisting of two unequal mass constituents within a vertical cylinder whose axis is maintained at a high temperature relative to the cylindrical wall, a slight separation of the components can be accomplished.

Clusius and Dickel[27] successfully operated a thermal diffusion tower for heavy isotopes. It consisted of a long vertical cylinder as shown in Figure 10.9. A hot wire at the axis maintained a temperature difference of about 600° C. between center and outer surface. The concentration of the heavier isotope increased slightly at the cool outer surface and at the same time a convection current carried the cooler gas downward and the lighter gas upward along the wire. Thus by withdrawing the gas at the axis at the top and passing it successively through additional similar stages an enrichment in the lighter isotope is obtained. The method works particularly well if the relative mass difference is appreciable. A single column two meters high was found[28] to separate almost completely the neon isotope of mass 20 from its sister isotopes whose masses are 21 and 22. Carbon 13 makes a stable tracer element in biological studies, and a single small tower will yield a few milligrams of the almost pure isotope per day.[29] The amount present after any reaction may be identified quantitatively by use of the mass spectrograph.

To obtain uranium enriched in the isotope 235, mammoth thermal diffusion towers were constructed and successfully operated.

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[27] H. Clusius and G. Dickel, *Naturwiss.*, 26, 546 (1938); 27, 148, 487 (1939).

[28] H. C. Urey, *Jour. App. Phys.*, 12, 270 (1941).

[29] A. O. Nier, *Phys. Rev.*, 57, 31 (1940).

*d. The Centrifuge.* High-speed centrifuges have been used with some success in the separation of isotopes.[30] The separation factor in this case depends on the masses of the two isotopes directly rather than on the square root of their ratio as for diffusion devices. By constructing the centrifuge as a tall cylinder, advantage can also be taken of the convection currents to aid in the separation.

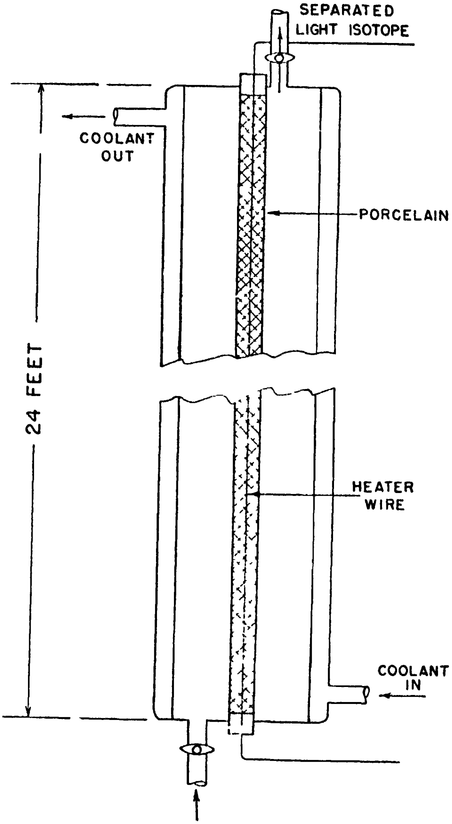

FIG. 10.9. Thermal tower for the separation of isotopes.

A separation factor $S$ may be defined as the ratio of the concentrations of light to heavy isotopes at the axis to the same ratio at the periphery of the rotor. Assuming that the vapor obeys the ideal gas law, it has been demonstrated that

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[30] J. W. Beams, *Rep. Phys. Prog. Phys. Soc.*, **8**, 31 (1942).

$$S = e^{(M_2 - M_1)\omega^2 r^2/2RT}$$

where $\omega$ is the angular velocity, $r$ the radius, $R$ the gas constant, $T$ the absolute temperature, and $M_2$ and $M_1$ the masses of the isotopes. It is evident that at high peripheral speeds this separation factor can be made significant.

**10.7. Neptunium and Plutonium.** By bombarding uranium with high energy deuterons, at least four isotopes of the next heavier element, now known as neptunium, could possibly be formed. For each of the two uranium isotopes a $(d, n)$ and a $(d, 2n)$ reaction might be expected. Since U 235 is present in such a small percentage, its products might not be observed. From uranium bombarded with 16 Mev deuterons McMillan and Abelson[31] first isolated a beta-emitting activity, whose half-life was about 2 days, obeying the chemistry expected for atomic number 93. When later produced in greater quantity, it was found that a daughter substance obeying the chemistry of element 94 could be taken from the neptunium.[32]

This product was called plutonium and was found to be an alpha emitter with a half-life of about 50 years. It was later shown that this isotope probably had the mass 238, thus arising in the original reaction, by the process, ${}_{92}\mathrm{U}^{238}(d, 2n){}_{93}\mathrm{Np}^{238}$, followed by a beta emission. At the same time the plutonium isotope of mass 239 was probably present and unnoticed because of its very long half-life of greater than 25,000 years. This isotope of plutonium might result from U 238 by both the $(d, n)$ and the $(d, p)$ reactions, both of which have a fairly high probability. It would also be produced by any neutrons present undergoing capture in U 238. The U 239 has a half-life of 23 minutes and converts by beta emission to neptunium

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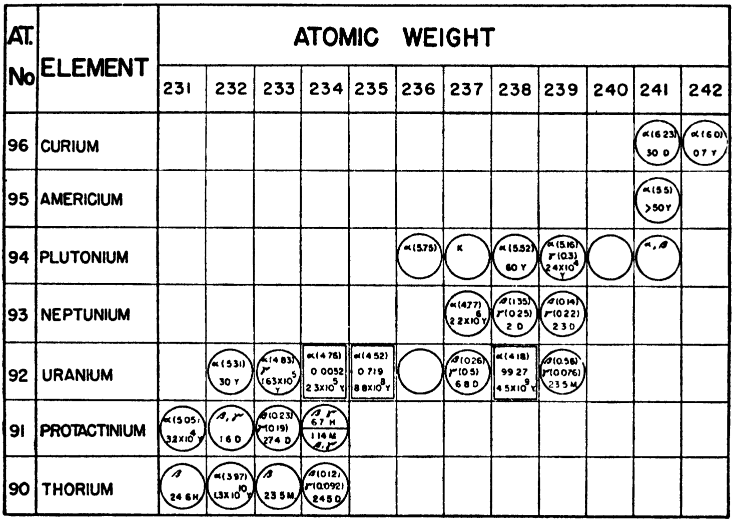
[31] E. McMillan and P. Abelson, *Atomic Energy Report*, Princeton Press (1945).

[32] G. Seaborg, J. Kennedy, and A. Wahl, *Atomic Energy Report*, Princeton Press (1945).

239, which in turn decays by beta emission of half-life 2.3 days to plutonium 239. Plutonium 239 is also an alpha emitter connecting with the uranium-actinium family. Most important is the fact that it undergoes fission with relatively low energy neutrons. These heavy radioactive isotopes are shown in Figure 10.10, together with their half-lives and the type of radiation emitted.



| AT. No | ELEMENT | ATOMIC WEIGHT | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 231 | 232 | 233 | 234 | 235 | 236 | 237 | 238 | 239 | 240 | 241 | 242 |
| 96 | CURIUM | | | | | | | | | | | α(6.23)<br>30 D | α(6.0)<br>0.7 Y |
| 95 | AMERICIUM | | | | | | | | | | | α(5.5)<br>>50 Y | |
| 94 | PLUTONIUM | | | | | | α(5.75) | K | α(5.52)<br>60 Y | α(5.16)<br>γ(0.3)<br>$2.4\times10^{4}$ Y | | α, β | |
| 93 | NEPTUNIUM | | | | | | | α(4.77)<br>$2.2\times10^{6}$ Y | β(1.35)<br>γ(0.25)<br>2 D | β(0.14)<br>γ(0.22)<br>2.3 D | | | |
| 92 | URANIUM | | α(5.31)<br>30 Y | α(4.83)<br>γ<br>$1.63\times10^{5}$ Y | α(4.76)<br>0.0052<br>$2.3\times10^{5}$ Y | α(4.52)<br>0.719<br>$8.8\times10^{8}$ Y | | β(0.26)<br>γ(0.5)<br>6.8 D | α(4.18)<br>99.27<br>$4.5\times10^{9}$ Y | β(0.56)<br>γ(0.076)<br>23.5 M | | | |
| 91 | PROTACTINIUM | α(5.05)<br>$3.2\times10^{4}$ Y | β, γ<br>1.6 D | β(0.23)<br>γ(0.19)<br>27.4 D | β, γ<br>6.7 H<br>1.14 M<br>β, γ | | | | | | | | |
| 90 | THORIUM | β<br>24.6 H | α(3.97)<br>$1.3\times10^{10}$ Y | β<br>23.5 M | β(0.12)<br>γ(0.092)<br>24.5 D | | | | | | | | |

Fig. 10.10. Isotopes of the very heavy elements.

**10.8. The Reactor or "Pile."** The first successful "reactor" or "pile" in which the unseparated isotopes of uranium maintained by themselves a continuous development of energy, was put in operation on December 2, 1942, at the University of Chicago.[33] The structure was an oblate spheroid built up in layers of graphite bricks. In alternate layers of the graphite were lumps of uranium, situated so as to be at the corners of a cubic lattice. The pile contained 12,400 lbs. of metal, together with some purified oxide, to complete the lattice. In order to control the rate of transformation, a number of rods of cadmium or boron steel were arranged so that they could be inserted or withdrawn. Because of their large absorption for thermal neutrons they could if inserted shield the uranium 235, and thus retard the action. A purely imaginary sketch of the arrangement is shown in Figure 10.11.

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[33] H. D. Smyth, *Atomic Energy Report*, Princeton Press (1945).

A term called the "multiplication factor," applying to the reactor, may be defined as the ratio of the neutron density with uranium in place to the corresponding density without the uranium. If this factor is greater than one, by any amount whatever, then the action will be self-sustaining. As a result of preliminary measurements made at Columbia University and supplementary calculations, the dimensions of a self-sustaining reactor had been predicted. As the assembly of the successive layers proceeded, a continuous measurement was made of the multiplication factor by the use of a boron-trifluoride neutron counter. With no arrestors in place, a multiplication factor *greater* than unity was found even before the last layers were in place.

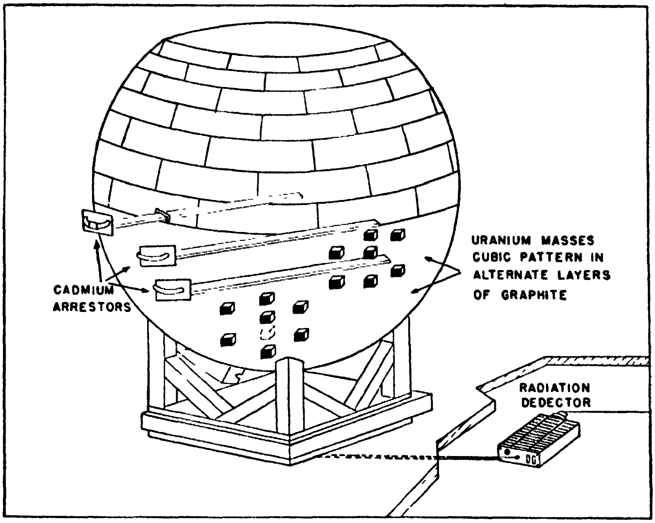

FIG. 10.11. An imaginary view of the first reactor at Chicago.

The large energy carried by the fission fragments must be dissipated in the total material of the reactor as thermal energy. As a consequence heat will be developed at a certain rate, which may be taken as the rating for the reactor. By December 12 this first reactor was run at a 200-watt rate.

For greater power outputs provision must be made to cool adequately the large active mass of material. To produce one gram of plutonium a day the pile must operate so as to have a continuous power output of about 1000 KW. A unit to produce this amount was put in operation at Clinton, Tennessee, on November 4, 1943. This unit was cooled by a circulating gas and the output was later stepped up to an increased power rate.

At Hanford, Washington, mammoth reactors utilizing liquid cooling were constructed. The first unit was put in operation in September 1944. With subsequent additions, production was brought up to a rate such that the power output was of the order of many thousands of KW.

The action in the reactor is a continuous conversion of U 235 by fission into elements of lesser atomic weight, lying somewhere near the center of the periodic table. At the same time many of the surplus neutrons are being captured by U 238. For each neutron so captured an atom of plutonium 239 is formed by subsequent beta decay. When the action has proceeded sufficiently, this fissionable plutonium and any other by-products formed may be separated chemically from the parent uranium. Because of the exceedingly strong radioactivity of the fission products utmost precaution must be exercised by the operators and the necessary chemical procedures are carried out by remote control.

**10.9. Radioactivity Accompanying the Action of the Reactor.** For each atom of U 235 undergoing fission two radioactive fragments are formed. In a modest reactor operating at 1000 KW, $3.37 \times 10^{16}$ particles are undergoing fission every second, forming $6.74 \times 10^{16}$ radioactive atoms. The half-lives of these numerous radioactivities formed are varied, but in general they would probably reach equilibrium, so that $6.74 \times 10^{16}$ radioactive disintegrations are occurring every second. Now $37.1 \times 10^9$ disintegrating atoms per second was termed a curie, so that the radioactivity here displayed could be expressed as 1.81 million curies. The gamma radiation from this tremendous source presents a difficulty in shielding. It also places a limitation on the use of small atomic energy plants where weight is an important factor.

This quantity of radium would emit gamma radiation alone, capable of producing 2500 "r" units in ten minutes at a distance of 10 meters from the source. This would be very close to a lethal exposure for any living organism.

In order that a "chain" reaction may proceed in a quantity of a pure fissionable isotope, it is essential that the mass be sufficient in relation to the total surface area. This relationship can be calculated and is illustrated graphically in Figure 10.12. On bringing the two non-active masses together properly, the critical size is exceeded and the action proceeds.

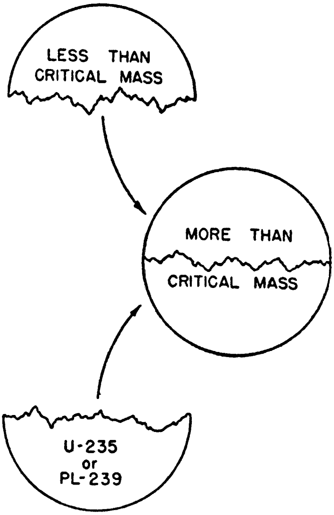

Fig. 10.12. Critical size of fissionable mass for the initiation of a chain reaction.

**10.10. Applications of the Reactor.** The same radioactivity, whose development limits the use of atomic energy in lightweight power units, might become a useful product of the action. On analyzing the metallic uranium after the self-sustaining reaction has been maintained for some time, a great number of radioactivities would be found present. Almost any specific radioactive element near the middle of the periodic table might be recovered in large quantities. Such products will have wide application in all other branches of science, particularly in medicine.

As shown in the purely imaginary sketch of Figure 10.13, the coolant enters at a low temperature and leaves at a higher temperature after absorbing heat. This is usually sufficient to an engineer for the continuous production of power.

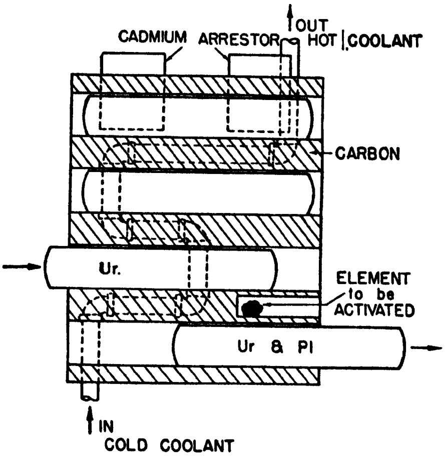

FIG. 10.13. Imaginary detail of a reactor.

While a reactor is building up radioactivity and supplying thermal energy it is at the same time building up as much or more fissionable plutonium as the U 235 that is lost.

The great advantage envisioned in the use of nuclear energy is the elimination of the transport difficulties usually associated with other fuels. For this reason it might conceivably play a tremendous role in altering the economy of a nation, particularly in the development of inaccessible areas. The first trial power plant operating from this source of energy is now under construction in Tennessee.

**10.11. The Enriched Reactor.** By using either plutonium or uranium enriched in isotope 235 as the active agent, in a pile or reactor, remarkable outputs may be achieved with an apparatus of relatively small dimensions. Such a device has been constructed and its performance reported in general terms.[34] The amazing result is that with a very few pounds of active agent in the form of a solution surrounded by a neutron reflector, so that the over-all dimensions are only about 4 feet on edge, disintegrations may occur at the rate of $10^{14}$ per second, giving an internal neutron flux of $10^{11}$ neutrons per $\text{cm}^2$ per sec. In the thermal neutron column connecting with the reactor the neutron flux may be as large as $10^7$ per $\text{cm}^2$ per sec.

This may be regarded as an indication of the tremendous possibility, within the reach of even a modestly endowed laboratory, should it ever happen that the vital fissionable material could be freed from its present military bondage. The danger of such general usage must, of course, never be underestimated. The radioactivity from such a small mass could be equivalent to that from thousands of grams of radium.

## QUESTIONS AND PROBLEMS

**1.** Assuming the possibility of utilizing the energy of both isotopes of uranium, compare the economic advantage in heating by uranium at $20 per lb., with coal at $10 per ton. Assume 180 Mev and 4 ev for the energies respectively per reaction.

*Answer:* 568:1.

**2.** Thermal neutrons are captured in U 235 but not in U 238. An average cross section for capture in unseparated uranium of $1.2 \times 10^{-24}$ $\text{cm}^2$ is observed. How thick a layer of pure U 235 would be required for $N$ incident thermal neutrons to produce $N$ fissions?

*Answer:* 0.378 cm.

**3.** The heat of combustion of TNT, $C_6H_2(CH_3)(NO_2)_3$ is 820,700 calories per gram molecular weight. What mass of plutonium would ideally release as much energy as a 2000-lb. mass of TNT?

*Answer:* 0.19 gm.

**4.** Assuming an average half-life of 1 hour for the radioactivities developed on the fission of plutonium, how many curies are represented in the source when 10 lbs. of plutonium undergo fission?

*Answer:* $1.19 \times 10^{11}$ curies.

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[34] R. F. Cristy, *Phys. Rev.*, **70**, 100 (1946).

5. Neglecting absorption in the air, and assuming the gamma rays to be equivalent to those from radium, at what maximum distance would a lethal dose of, say, 3000 "r" units be received during the first hour from the above source? Assume no dispersion of the source.

*Answer:* 5850 meters.

6. On considering the absorption of the air, assuming standard conditions, what would be the dosage at the above determined distance?

*Answer:* For $\mu/\rho = 0.058$ cm$^2$/gm.) $1.23 \times 10^{-15}$ "r" per min.

## CHAPTER 11

# SOME APPLICATIONS OF RADIOACTIVITY

**11.1. Historical.** With the discovery of natural radioactivity in 1896, it might have been expected that widespread use of the phenomenon would be found in other branches of science. The first application came in the field of medicine. In 1900, Walkhoff and Giesel announced certain physiological effects in tissue exposed to the new radiation. Madame Curie and Becquerel had both received superficial burns from close contact with the active matter. Alert to this surprising power of the rays, Pierre Curie in 1901 collaborated with two medical men, Prof. Bouchard and Prof. Balthazard in studying the action of radium on animals. In 1902 they concluded that "by destroying diseased cells, radium cured growths, tumors, and certain forms of cancer." French practitioners then began the treatment of diseased persons with tubes of emanation loaned by Pierre and Marie Curie. To enlarge this activity the first gram of radium was successfully separated from about 8 tons of pitchblende residue, largely through the untiring efforts of Madame Curie.

Not until 1913, when Paneth and Hevesy[1] used radium D as a tracer element in chemical reactions, was the possibility of the advantageous use of radioactive elements in other branches of science recognized.

With the discovery of induced radioactivity in 1934, and its subsequent development, it became possible to render any element in the periodic table radioactive. The half-lives of these activities vary from a fraction of a second up to many years.

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[1] F. Paneth and G. Hevesy, *Akad. Wiss. Wien*, **122**, 1001 (1913).

Some emit only beta rays or positrons while others emit gamma rays or a combination of both types of radiation. The availability of this wide variety of radioactive bodies stimulated their use in all related fields of science. Within a few years an avalanche of papers was appearing attesting to the efficacy of this new agent. It is apparent that by using radioactive, or tagged, detectible elements the behavior of matter in many reactions could be followed in a manner quite impossible without the radioactivity.

A few illustrations of the usefulness of radioactivity in some related branches of science will be presented. This is not intended to be a complete report on any investigation or to cover all of the applications.

**11.2. Astronomy—Solar Energy.** Any connection between astronomy and nuclear physics might seem exceedingly remote. It is true, however, that only recently, by using the information gained in studying nuclear reactions, has it become possible to answer one of the long-standing puzzling questions, namely, what keeps our sun at a constant temperature.

The solar constant of radiation at the surface of the earth is about 1.94 calories per $cm^2$ per minute. From this, one can calculate the total energy radiated by the sun in any interval of time. By assuming a reasonable value of the thermal capacity of the sun, one finds that the total radiant energy should be sufficient to reduce the temperature about 15° C. per year if the sun were simply a cooling body. Actually no drift in the solar temperature has been observed. It must therefore follow that some processes are taking place on the sun so as to release energy as fast as it is being radiated.

From a knowledge of nuclear reactions and conditions presumed to exist at great depths below the surface of the sun, H. Bethe was able to provide an answer.[2] If the temperature and pressure are sufficiently high and hydrogen is present together with some carbon, then the following nuclear reactions might take place:

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[2] H. A. Bethe, *Phys. Rev.*, 54, 248 (1938); 55, 434 (1939).

$$_6C^{12} + {}_1H^1 \rightarrow {}_7N^{13} \rightarrow {}_6C^{13} + {}_1e$$

$$_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14}$$

$$_7N^{14} + {}_1H^1 \rightarrow {}_8O^{15} \rightarrow {}_7N^{15} + {}_1e$$

$$_7N^{15} + {}_1H^1 \rightarrow {}_8O^{16} \rightarrow {}_6C^{12} + {}_2He^4$$

The average specific gravity of the sun is about 1.4, yet at a sufficient depth it is not unreasonable that it might be 80 times as large. Under this condition the temperature must be about 20 million degrees C. For the concentration of hydrogen known to exist, namely about 35% by weight, Bethe concluded that nuclear energy is being released at the rate of 100 ergs per gram per second. This alone is sufficient to account for the total radiation. In this reaction carbon serves as a catalyst in the formation of helium from hydrogen. The carbon unites cyclically with protons, becoming in turn nitrogen and oxygen. The excited oxygen finally splits up into an alpha particle and a carbon atom identical with the original. As stars grow older their hydrogen content thus diminishes.

Some speculation might be made regarding the age of the sun by assuming that all of its present helium has been derived from hydrogen. Spectroscopically it is possible to estimate the present abundance of helium. By combining this with its known present rate of formation an estimate of several billion years results.

**11.3. Botany.** *a. Transport of Fluids.* Radioactive salts in solution may be taken up by the roots of plants and a subsequent analysis made of their location by noting the activity in an exploring Geiger tube. In this way by a single experiment it was shown that the long-held notion of upward transport in plants might need revision.[3] If, as had been supposed, the upward transport takes place through the woody part of the stem alone, then on removing a section of the wood of the stem no transfer should occur. Gustafson found evidence that the radioactive material was still being carried upward, indicating an upward transport in the bark. The question is still not entirely resolved, as a somewhat contrary conclusion was reached by other workers using the same technique.[4]

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[3] F. Gustafson, *Science*, 85, 482 (1937); *Jour. App. Phys.*, 12, 327 (1941).

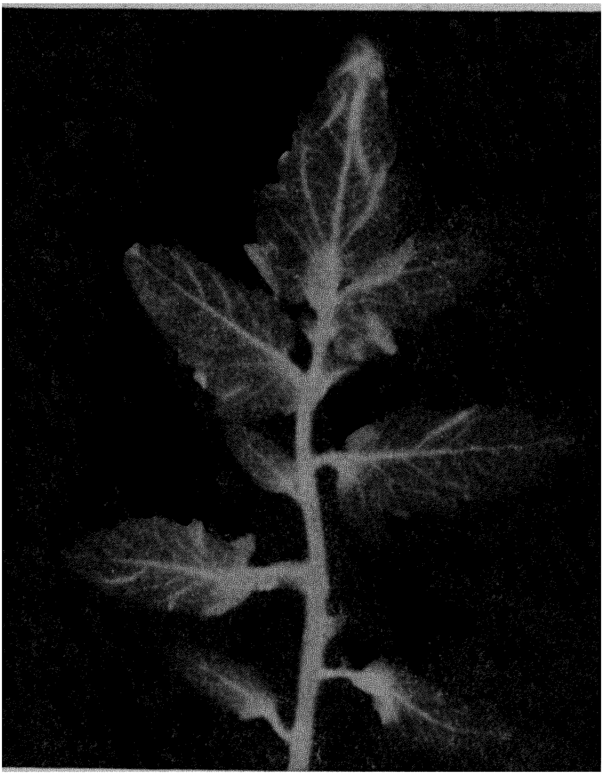

FIG. 11.1. Auto-radiogram of selectively absorbed radiophosphorus.

*b. Photosynthesis.* The reactions by which carbon dioxide in the presence of light and water proceed to form sugars, have been little understood. By using carbon dioxide consisting of radioactive carbon 11, whose half-life is only 21 minutes, Ruben and Kamen[5] have been able partly to solve the difficult chemistry associated with the process. They found that the carbon dioxide united reversibly in a non-photochemical reaction with a heavy molecule of the type *RH* where *R* is an atomic aggregate of large total weight. Thus,

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[4] P. R. Stout and J. R. Hoagland, *Amer. Jour. Biol.*, 26, 320 (1939).

$$RH + CO_2 \leftrightarrows R\,COOH$$

This carboxyl molecule unites photochemically with water to form a possible sugar, as

$$R\,COOH + H_2O + h\nu \rightarrow R\,CH_2OH + O_2$$

The formation of the sugar is thus a multiple reaction, quite different from that which had been classically assumed.

*c. Selective Absorption.* The selective absorption of a given radioactive element in any particular tissue of the plant may be revealed by a photographic technique. Figure 11.1 is an "auto-radiogram" of a tomato plant that had been placed in a solution containing dissolved radiophosphorus.[6] After the lapse of an appropriate time the plant is removed from the solution and placed firmly against the photographic emulsion, in a darkened room. The blackening of the plate is a measure of the abundance of the radioactive element in the contiguous part of the plant. In the figure it is quite clear that the phosphorus accumulates in the stems and the conduction system of the leaves. It is also found abundantly in the seeds of the fruit.

**11.4. Chemistry.** *a. Adsorption.* The phenomenon of adsorption, in which solids take up on their surfaces, gases, liquids, or other dissolved solids, has been difficult to understand. Various theories have been offered. In some cases it has been proposed that the action is a solution, and in others a chemical combination is assumed to occur. By using radioactive sodium and bromine as tracer elements it has been demonstrated[7] that in the case of eosin and erythrosin dyes the adsorption consists entirely of an exchange between the negative ions of the solution and the negative ions of the adsorbent.

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[5] M. Kamen and S. Ruben, *Jour. App. Phys.*, 12, 326 (1941).

[6] D. Arnon, P. Stout, and F. Sipos, *Amer. Jour. Bot.*, 27, 791 (1940).

*b. Synthesized Elements.* There were still four unknown elements between hydrogen 1 and uranium 92 in 1937: namely, those of atomic number 43, 61, 85, and 87. The chemistry of these elements could be predicted from their position in the periodic table and hence also their most probable source. All attempts to isolate and identify them were unsuccessful. By bombarding neighboring elements in the periodic table with various projectiles, radioactive isotopes of each of these elements, except 87, have now been positively identified. In some cases the chemistry of the element has been found to be somewhat different than had been predicted. Element 87 has been found by Mlle. Perey as a branching product in the actinium series.[8]

The very heavy elements of atomic number 93, 94, 95, and 96, of course, were first known only as a result of nuclear reactions. A trace of plutonium has since been found to be present in the pitchblende from the Great Bear Lake deposit.

By bombarding gold with deuterons an isotope of mercury is formed that is quite different from ordinary mercury.[9] Gold has a single isotope of mass 197. By a $(d, p)$ reaction radioactive gold 198, whose half-life is 2.7 days, is formed. On the emission of a beta particle, stable mercury consisting of a single isotope of mass 198 is formed. Ordinary mercury has an atomic weight of 200.6 and consists of 7 isotopes varying from 196 to 204 in mass. Sufficient mercury 198 has been made in this way to make spectroscopic studies. The radiation has been proposed as a spectroscopic standard of length, since it is free from hyperfine structure and isotope shift.

[7] A. Newton and K. Fajans, *Jour. App. Phys.*, **12**, 306 (1941).

[8] Mlle. Perey, *Comptes Rendus*, **208**, 97 (1939).

[9] J. Wiens and L. Alvarez, *Phys. Rev.*, **58**, 1005 (1940).

Many other applications of radioactivity to chemical problems, in the fields of reaction rates, surface studies, molecular structure, solubility, and catalysis have been successfully consummated.

*c. Alchemy.* The transmutation of base metals into gold has through the ages been the goal of a certain group of investigators; often the most erudite of their generation. From time to time success has been reported, only to be proven later to be unfounded.

The possibility of inducing transmutations by bombardment, with high energy particles being well established, it naturally became of interest to achieve this long-sought goal and create gold from another element. This was first accomplished [9a] in 1936. The lustre of the achievement was somewhat dulled by the fact that the parent element in the reaction is platinum. The process as carried out is illustrated by the following equation:

$$_{78}\mathrm{Pt}^{196} + {}_{1}\mathrm{H}^{2} \rightarrow {}_{78}\mathrm{Pt}^{197} + {}_{1}\mathrm{H}^{1};$$

$$_{78}\mathrm{Pt}^{197}\ (18\ \text{hr. half-life}) \rightarrow {}_{79}\mathrm{Au}^{197} + {}_{1}e$$

The radioactive platinum 197 formed in the bombardment decays by beta emission to ordinary gold.

**11.5. Engineering.** *a. Radiology.* With the development of semi-portable Van de Graaf generators, and betatrons capable of delivering X-rays up to 5 Mev, defects in any engineering structure, whose thickness is not greater than about 10 inches of steel, can be expeditiously located.

Certain of the radioactive isotopes emit very penetrating gamma radiation. Cobalt 60 has a half-life of 5.3 years and emits gamma radiation having an energy 1.30 Mev. An isotope of yttrium of mass 88 is a by-product in the making of radiostrontium by the bombardment of strontium with deuterons.[10] It has a half-life of 100 days and emits gamma rays of energy 2.8 Mev. Because of the minute size of a strong specimen, it can often be used advantageously to take photographs such as through a few inches of steel, in positions inaccessible to other larger equipment.

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[9a] J. M. Cork and E. O. Lawrence, *Phys. Rev.*, 49, 788 (1936).

[10] L. DuBridge and J. Marshall, *Phys. Rev.*, 58, 7 (1940).

*b. Thickness Measurement.* Radioactivity may be employed to determine the thickness of metallic walls or plates that are not susceptible to measurement by calipers or other devices. By placing a calibrated radioactive source on one side of the wall and a receiver on the other, then the reading observed falls off with increasing thickness both because of increased absorption and decreased solid angle. By choosing a source emitting radiation of the proper energy, a sensitivity and speed of operation comparable with that of any other instrument may be attained in the measurement.

An interesting modification of this apparatus permits the measurement of such plates when their back surface is not accessible. The scattering of neutrons or gamma radiation depends upon the amount and kind of matter present. The radiation from a fixed source placed near the plate will be scattered back to a contiguous receiver in amounts proportional to the thickness of the scatterer.

Arrangements of this sort have been successfully utilized in oil-well "logging." In this case a source of neutrons and a detector shielded from the direct radiation are mounted as a unit and lowered into the well. The amount of back-scattered neutron radiation depends largely on the hydrogen content of the material contiguous to the walls of the drill hole. In this way a complete survey of the well can be made by observing the intensity of the back-scattered radiation as the unit reaches successive depths.

**11.6. Metallurgy—Atomic Diffusion.** In the alloying, case-hardening, or welding of metals it is of interest to know to what extent the atoms of one element are able to diffuse into another metal or into its own solid phase. A technique to study the behavior of the natural radioactive elements in contact with other elements was developed by von Hevesy.[11] Since any of the known elements may now be made radioactive, such investigations of self-diffusion can be carried out for every metal.

A rather complete study of the diffusion of copper atoms in copper as a function of the temperature was carried out by Raynor.[12] His results are shown on the semi-logarithmic plot of Figure 11.2, in which the diffusion coefficient as ordinate is plotted against the reciprocal of the absolute temperature $T$. It may be recalled that almost an identical relationship exists between the vapor pressure of a liquid and its temperature. Thus the diffusion of the metallic ions may be quite similar

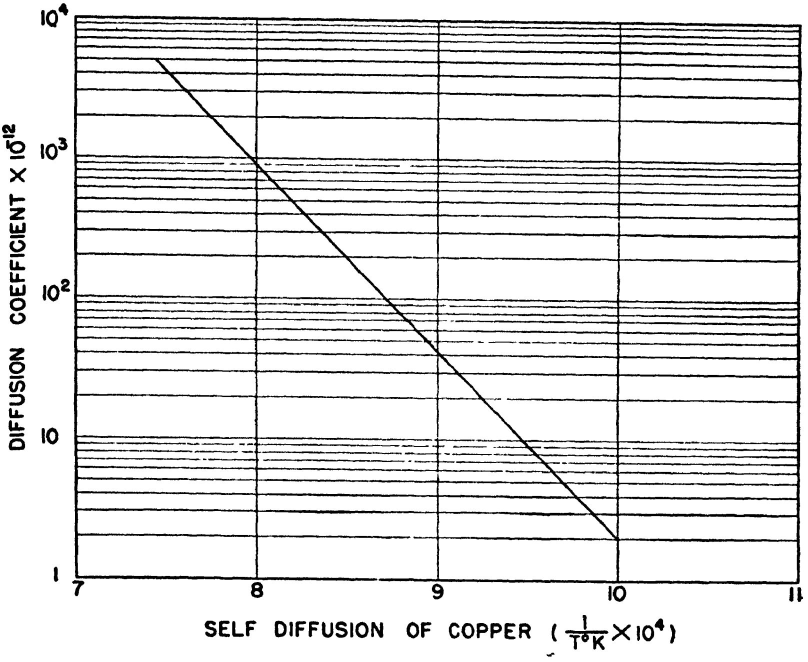

Fig. 11.2. The self-diffusion of copper as affected by the temperature.

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[11] G. von Hevesy, *Trans. Faraday Soc.*, **34**, 841 (1938); *Zeits. f. Electech.*, **26**, 363 (1920).

[12] C. Raynor, L. Thomassen, and L. Rouse, *Proc. Amer. Soc. Metals*, **30**, 313 (1942).

to the process of evaporation. The diffusion coefficient $\eta$, which represents the number of atoms diffusing through unit area in a given time, because of the observed linear relationship, is representable as

$$\log \eta = A + \frac{B}{T}$$

where $A$ and $B$ are constants. Similar measurements have been made on bismuth, gold, lead, and zinc.[13]

**11.7. Medicine.** *a. Radiation Therapy.* Any ionizing radiation will, if in sufficient intensity, kill all living cells exposed to it. During the process of growth the susceptibility of cells to radiation is greater than when they are in the fully developed state. In cancerous tissue the abnormal cells are undergoing rapid growth. The possibility therefore exists that by just the right dosage the abnormal tissue might be eliminated without seriously damaging the normal cells. There has been some reason to hope[14] that for neutron radiation the difference in lethal thresholds for the diseased and well tissue might be relatively greater than when using X-rays or gamma rays. Should this prove to be true, its importance would be incalculable.

It is not unreasonable to suppose that neutron radiation would behave differently than X-rays on absorption. A neutron gives its energy to a recoil proton which travels only a short distance with intense ionization along its path. An X-ray photon, on the other hand, gives rise to an electron whose specific ionization is relatively small. The recoil proton might kill any single diseased cell through which it travels, whereas it might require the cumulative effect of several recoil electrons to produce the same effect.

The same "roentgen" meter used in measuring the intensity of X-rays in "r" units may be employed to measure the neutron dosage. The intensity is then expressed in "n" units. It is found that a given number of "n" units of neutron radiation is equivalent to a dosage of from 2 to 10 times as many "r" units of X-rays in its biological effect.

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[13] H. Day, F. Banks, and P. Miller, *Phys. Rev.*, 57, 1067 (1940); 59, 376 (1941).

[14] J. H. Lawrence, *Amer. Jour. Roentg.*, 48, 283 (1942).

*b. Specific Absorption.* It is well known that various tissues of the body will take up selectively specific elements from the circulating fluids. Thus after an intravenous injection of iodine, this element is found in relatively high percentages in the thyroid, liver, spleen, and heart. Phosphorus is similarly absorbed by bone marrow, and calcium and strontium are taken up in large measure by the bones. It is evident that by making the absorbed element radioactive, local destruction of the absorbing tissue may be accomplished with no general ill effects. In leukemia, a disease in which the white blood corpuscles multiply abnormally, some measure of control can be achieved by a dosage of from two to eight millicuries of radiophosphorus. This element on absorption in the bone marrow can destroy the cells in their formative stage and thus control the count of the white blood corpuscles.

Similarly, radioactive strontium 89 has been successfully used in the treatment of bone tumors. This isotope emits solely beta particles whose maximum energy is 1.3 Mev with a half-life of 55 days. When strontium lactate is administered intravenously as much as 35% of the dose becomes fixed in the skeleton. Figure 11.3*A* is an ordinary photograph and Figure 11.3*B* is an "auto-radiogram" of a section through the amputated knee of a patient previously given radioactive strontium. It is apparent that the radioactive material has accumulated preponderantly in the neoplastic tissue and in the epiphyseal line where growth is taking place. This is just the tissue which it is desired to have receive radiation.

Neutron radiation is effectively captured by particular elements, such as boron, lithium, and cadmium. If any of these elements could be preadministered to specific tissue, then on radiation by neutrons, intense local ionization would result from the energetic alpha particles or protons liberated in the accompanying reaction. Some difficulty exists in administering and preventing the diffusion of the specific absorbing material.[15] It is, however, a method that might have some particular applications in therapy.

*c. Tracer Studies.* The radioactive isotope of an element behaves chemically exactly like the normal atoms of that element. It differs only that on its disruption its presence is revealed. If administered in such small quantities that it does not alter in any way the physiological process being studied it may still disclose the behavior of the entire material of which it is a part. It is easy to visualize the importance of this technique in the study of metabolism and circulatory and chemical processes in the human body. Illustrative of this type of ap-

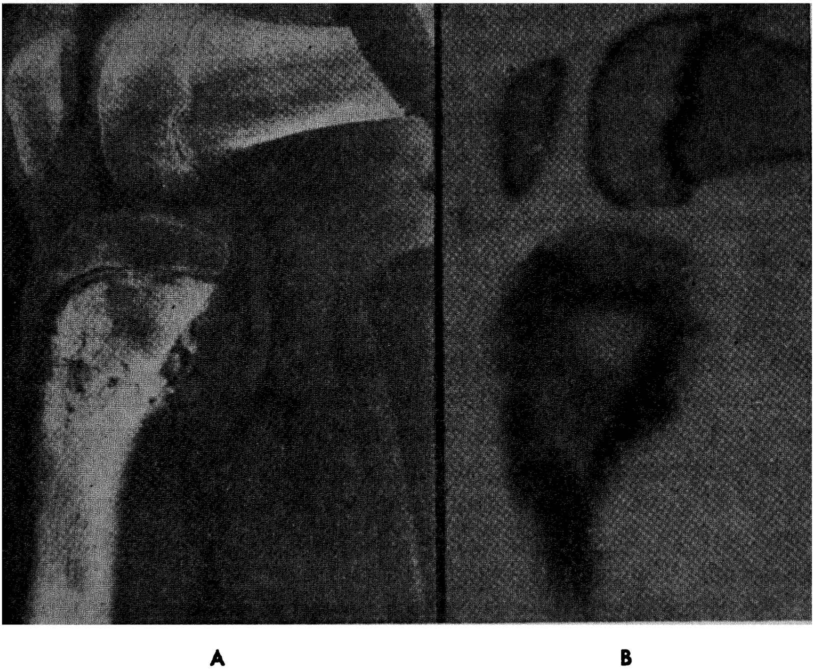

FIG. 11.3. Auto-radiogram of section of amputated knee, indicating selective absorption of radio-strontium.

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[15] P. Kruger, *Proc. Nat. Acad. Sci.*, 26, 181 (1940).

plication is the study made of the chemical reactions associated with muscular activity.[16] The complicated chemical transformations occurring during the activity of the muscle have been greatly clarified.

**11.8. Mineralogy—The Color of Crystals.** It has long been known that the color of crystals can be altered by exposing them to any ionizing radiation, such as X-rays, cathode rays, or gamma rays. Even more effective in producing alterations in color on the surface of a crystal is exposure to the deuteron beam of the cyclotron.[17] The importance of coloration is well illustrated by considering two chemically identical crystals, aquamarine and emerald. The latter by virtue of its color has a valuation more than one hundred times that of the former.

The most valued diamonds have been the very rare green crystals. On exposure to deuterons for a few seconds the most inferior amber-tinted diamond takes a permanent green tint equal to that of the best natural gems. On heating to a very high temperature the amber tint may be restored.

The coloration induced in such a crystal as rock salt, varying in shade from amber to black, may be used as an indicator of the intensity of radiation. Too strong radiation or heating to about 220° C. will restore the original clearness.

**11.9. Zoology—Mutations.** The nucleus of the living cell contains a certain number of threadlike structures known as chromosomes. In the chromosomes are minute entities called "genes." The genes occur in pairs, one member being derived from each parent. When the cell divides, each chromosome and each gene also divide so that each daughter cell resembles the parent. Destruction or alteration of the genes alters the characteristics of the cell. If the change occurs in a germ cell the alteration is transmitted to all subsequent generations, provided the change is compatible with life. This transmission to a daughter cell of altered characteristics is termed a mutation. This phenomenon undoubtedly plays an important role in evolution.

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[16] J. Sachs, *Amer. Jour. Physiol.*, 129, 227 (1940).

[17] J. M. Cork, *Phys. Rev.*, 62, 80, 494 (1942).

Mutations in nature occur spontaneously, but not frequently. The effect of ionizing radiation is to increase markedly the frequency of mutations, which might naturally occur. Thus geneticists are able to observe in a short time those changes which by spontaneous mutation would occur only infrequently. This fact was first demonstrated by Muller for X-rays in 1927,[18] using as subject material the fruit fly, drosophila. The same fundamental principles [19] are applicable to all living beings, including man. A profusion of papers on this subject has since appeared, using in some cases gamma rays and neutron radiation, all with similar effects.

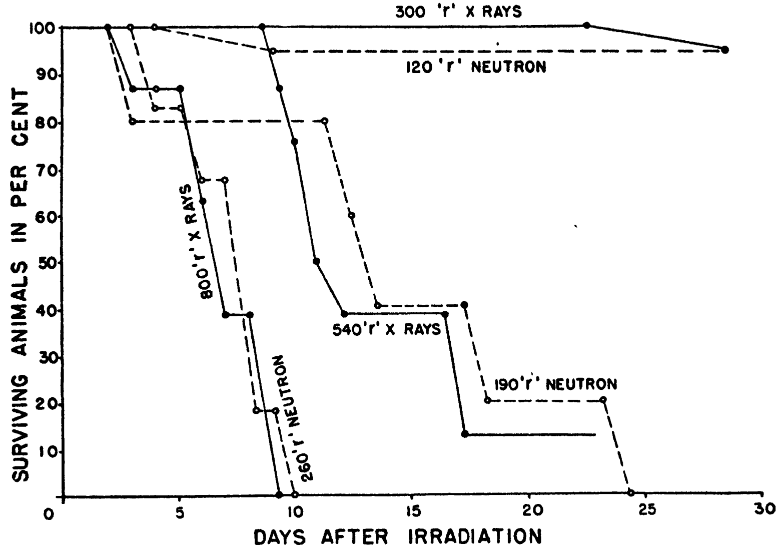

FIG. 11.4. The relative effect of neutrons and X-rays on the survival of drosophila

The relative effect of neutrons and X-rays in producing biologic effects is illustrated by Figure 11.4. This figure summarizes the survival of organisms, some of which were exposed to various intensities of X-rays and others to varying amounts of neutron radiation, as measured by the same X-ray "r" meter.[20] It is apparent that dosages of 120 "n" of neutrons and 300 "r" of X-rays produced little if any increase in what might be termed the natural death rate. Ninety per cent of the radiated insects were alive after 30 days. On increasing the dosages the death rate materially increased, so that those animals which received 800 "r" units of X-rays or 260 "n" of neutrons were all dead before the end of 10 days after irradiation. The factor relating the lethal effect of 1 "n" of neutrons and 1 "r" of X-rays appears in this case to be about three to one. The value of this ratio varies with the biologic subject, being greater for those organisms possessing a large hydrogen content.[21]

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[18] H. J. Muller, *Science*, 67, 82 (1928).

[19] See G. Failla, *Jour. App. Phys.* 12, 279 (1941).

## QUESTIONS AND PROBLEMS

**1.** A dosage of 10 millicuries of radiophosphorus is applied intravenously to a patient whose blood volume is 4 liters. Assuming that 70% of the activity remains uniformly distributed in the blood at the end of 30 minutes, how many beta particles per second would be emitted by a $cm^3$ of the withdrawn blood?

*Answer:* 64,925 particles/sec.

**2.** A source of radiosodium is assayed as 90 millicuries. It is administered to a patient 45 hours later. What is the activity at that time?

*Answer:* 9.3 millicuries.

**3.** At 10 Mev a deuteron bombardment of 35 microampere hours on pure phosphorus will produce one millicurie of radioactive $P^{32}$. A bombardment of a refractory iron-phosphide ($Fe_2P$) probe is carried out with a cyclotron beam of 250 microamperes. Allowing $15.00 per hour for the cost of operation, what is a reasonable charge per millicurie of phosphorus? What will happen in the iron?

*Answer:* $9.72 per mc.

**4.** The cross section for the reaction ${}_4Be^9\ (d, n){}_5B^{10}$ is $1.2 \times 10^{-25}$ $cm^2$. A deuteron beam of 60 microamperes traverses a thin beryllium target, 5 mils (0.005″) in thickness. How many neutrons per second will pass through a normal area 10 cm on edge, situated 60 cm from the target, assuming a uniform distribution? Compare the energy of a neutron in the forward direction with that of a neutron ejected normal to the beam.

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[20] J. Lawrence, P. Aebersold, and E. O. Lawrence, *Proc. Nat. Acad. Sci.*, 22, 543 (1926).

[21] R. E. Zirkle and I. Lampe, *Amer. Jour. Roentg.*, 39, 613 (1938).

*Answer:* $15.5 \times 10^7$ per sec.

**5.** The absorption coefficient of neutrons in tissue is 0.14 $\text{cm}^{-1}$. What is the cross section for the absorption process, assuming the tissue to behave as water, and hydrogen to be the absorbing agent?

*Answer:* $1.95 \times 10^{-24}$ $\text{cm}^2$.

**6.** The average specific gravity of the sun is 1.4 and its diameter is 860,000 miles. The solar radiation constant at the earth is 0.135 joules per $\text{cm}^2$ per sec. and the average distance to the sun is 93 million miles. At what total rate does the sun lose radiation? At what rate does the total mass change?

*Answer:* $3.8 \times 10^{26}$ joules/sec or $4.2 \times 10^{12}$ gms/sec or $4.6 \times 10^6$ tons/sec.

**7.** If the above energy is derived from the synthesis of helium from hydrogen, at what rate is helium being produced in the sun?

*Answer:* $5.9 \times 10^{14}$ gms/sec.

## CHAPTER 12

# TABLE OF ISOTOPES

By using various modes of excitation, over four hundred radioactive isotopes of the 96 elements have been created. It is frequently desirable to know the half-lives and type of radiation emitted by certain of these, without too much searching in the literature. This information is assembled in the following table.

The information presented has been derived in part from the original papers and in part from other previously prepared summarizing tables. Among these may be mentioned the following:

M. Curie, A. Debierne, A. Eve, H. Geiger, O. Hahn, S. Lind, St. Meyer, E. Rutherford, and E. Schweidler, *Rev. Mod. Phys.*, **3**, 427 (1931).

W. B. Lewis and B. Bowden, *Proc. Roy. Soc.*, **145**, 235 (1934).

M. Holloway and M. S. Livingston, *Phys. Rev.*, **54**, 18 (1938).

F. W. Aston, *Isotopes*, Longmans (1932, 1942).

J. M. Cork, "Table of Isotopes," *Handbook of Phys. and Chem.* (1940).

R. D. Evans, "Isotopes," *Medical Physics*, Year Book Pub. Co. (1944).

G. T. Seaborg and J. Livingood, *Rev. Mod. Phys.*, **12**, 30 (1940).

G. T. Seaborg, *Rev. Mod. Phys.*, **16**, 1 (1944).

Isotope Committee Report, *Science*, **103**, 697 (1946).

In the following table, the energy of each type of radiation is shown in the accompanying parenthesis. The symbol *K* is used to denote the "K" electron capture process by the nucleus and *I* represents internal conversion of gamma radiation.

The designations $\gamma$, $e^-$, and $e^+$ are for gamma ray, electrons, and positrons, respectively. The percentage abundance of the stable isotopes is presented in the column headed as %. Half-lives are designated as *S*, *M*, *H*, *D*, and *Y* for seconds, minutes, hours, days, and years.

| Z | *Element Name* | *N* | *Mass* | *% Abundance* | *Half-Life* | *Radiation (Mev)* | *Reference* * |
|---|---|---|---|---|---|---|---|
| 0 | Electron .. .. | 0 | 0 000548 | | | | |
| 0 | Neutron... | 1 | 1 00893 | | | | |
| 1 | Proton . . . | 1 | 1 007582 | | | | |
| 1 | Hydrogen .. | 1 | 1 008130 | 99 98 | | | |
| | | 2 | 2 014722 | 0 02 | | | |
| | | 3 | 3 01705 | | 31 *Y* | $e^-$ (0.015) | 1, 2 |
| 2 | Alpha . . | 4 | 4 002764 | | | | |
| 2 | Helium...... | 3 | 3 01711 | $\sim 10^{-9}$ | | | |
| | | 4 | 4.00386 | ~100 | | | |
| | | 6 | 6.0209 | | 0.8 *S* | $e^-$ (3.7) | 3, 4, 5 |
| 3 | Lithium.... | 6 | 6 01682 | 7 9 | | | |
| | | 7 | 7.01784 | 92 1 | | | |
| | | 8 | 8.02497 | | 0.88 *S* | $e^-$ (12.0) | 6, 7, 8 |
| 4 | Beryllium... | 7 | 7 01908 | | 43 *D* | $\gamma$ (0.485), *K* | 9, 10, 12 |
| | | 8 | 8.007766 | | | | |
| | | 9 | 9.01486 | 100 | | | |
| | | 10 | 10.01671 | | $7 \times 10^3$ *Y* | $e^-$ (0.5), $\gamma$ (0.5) | 13 |
| 5 | Boron....... | 10 | 10 01633 | 18 4 | | | |
| | | 11 | 11 01295 | 81.6 | | | |
| | | 12 | 12.0168 | | 0.022 *S* | $e^-$ (12.0) | 6, 7, 14 |
| 6 | Carbon . ... | 10 | 10 01833 | | 8.8 *S* | $e^+$ (3.4) | 15 |
| | | 11 | 11 01499 | | 20 5 *M* | $e^+$ (0.95) | 15, 16, 17 |
| | | 12 | 12 00386 | 98 9 | | | |
| | | 13 | 13 00766 | 1.1 | | | |
| | | 14 | 14.00780 | | $10^3$ *Y* | $e^-$ (0.145) | 18 |
| 7 | Nitrogen..... | 13 | 13.01005 | | 9.93 *M* | $e^+$ (0.92, 1 2),<br>$\gamma$ (0 28) | 19, 20, 21, 22 |
| | | 14 | 14 00756 | 99 62 | | | |
| | | 15 | 15 00495 | 0 38 | | | |
| | | 16 | 16.00645 | | 8.0 *S* | $e^-$ (6.0) | 23, 4 |

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* References are on pp. 291–4.

| *Z* | *Element Name* | *N* | *Mass* | *% Abundance* | *Half-Life* | *Radiation (Mev)* | *Reference* |
|---|---|---|---|---|---|---|---|
| 8 | Oxygen. . . . . . | 15 | 15.0078 | | 126 *S* | $e^+$ (1.7) | 23, 25 |
| | | 16 | 16.000 | 99.76 | | | |
| | | 17 | 17.00449 | 0.04 | | | |
| | | 18 | 18.00369 | 0.20 | | | |
| | | 19 | | | 31 *S* | $e^-$ | 4, 25 |
| 9 | Fluorine. . . . . | 17 | 17.0076 | | 70 *S* | $e^+$ (2.1) | 27, 28, 29 |
| | | 18 | 18.0056 | | 112 *M* | $e^+$ (0.7) | 19, 30, 31 |
| | | 19 | 19.00452 | 100 | | | |
| | | 20 | 20.0063 | | 72 *S* | $e^-$ (5.0), $\gamma$ (2.2) | 3, 6, 32, 33 |
| 10 | Neon. . . . . . . | 19 | 19.00798 | | 20.3 *S* | $e^+$ (2.20) | 34 |
| | | 20 | 19.99896 | 90.0 | | | |
| | | 21 | 20.99968 | 0.27 | | | |
| | | 22 | 21.99864 | 9.73 | | | |
| | | 23 | 23.0005 | | 40 *S* | $e^-$ (4.1) | 26, 35 |
| 11 | Sodium. . | 21 | | | 23 *S* | | 35, 36 |
| | | 22 | 22.00032 | | 3 *Y* | $e^+$ (0.58) | 37, 38 |
| | | 23 | 22.99644 | 100 | | | |
| | | 24 | 23.99774 | | 14.8 *H* | $e^-$ (1.4),<br>$\gamma$ (1.38, 3.73) | |
| | | 25 | | | 62 *S* | $e^-$ (2.8), $\gamma$ (0.035) | 42 |
| 12 | Magnesium | 23 | 23.00055 | | 11.6 *S* | $e^+$ (2.82) | 34, 42 |
| | | 24 | 23.99189 | 77.4 | | | |
| | | 25 | 24.99277 | 11.5 | | | |
| | | 26 | 25.99062 | 11.1 | | | |
| | | 27 | 26.99256 | | 10.2 *M* | $e^-$ (1.8),<br>$\gamma$ (1.02, 0.84) | 26, 43, 44 |
| 13 | Aluminum. | 26 | 25.99446 | | 7.0 *S* | $e^+$ (2.99) | 34, 38, 45 |
| | | 27 | 26.99069 | 100 | | | |
| | | 28 | 27.99077 | | 2.4 *M* | $e^-$ (3.3), $\gamma$ (1.8) | 26, 43, 46 |
| | | 29 | 28.9890 | | 6.7 *M* | $e^-$ (2.5) | 47 |
| 14 | Silicon . . | 27 | 26.99711 | | 4.92 *S* | $e^+$ (3.64) | 36, 48 |
| | | 28 | 27.98727 | 89.6 | | | |
| | | 29 | 28.98635 | 6.2 | | | |
| | | 30 | 29.98399 | 4.2 | | | |
| | | 31 | 30.9862 | | 170 *M* | $e^-$ (1.8) | 26, 27, 28 |
| 15 | Phosphorus . | 29 | 28.9135 | | 4.6 *S* | | 49 |
| | | 30 | 29.9882 | | 2.55 *M* | | 50, 51, 52 |
| | | 31 | 30.9839 | 100 | | | |
| | | 32 | 31.9841 | | 14.3 *D* | $e^-$ (1.69) | 26, 40, 53 |
| 16 | Sulphur. . . | 31 | 30.98965 | | 3.18 *S* | $e^+$ (3.9) | 49, 48 |
| | | 32 | 31.9823 | 95.1 | | | |
| | | 33 | 32.9818 | 0.74 | | | |

| Z | Element Name | N | Mass | % Abundance | Half-Life | Radiation (Mev) | Reference* |
|---|---|---|---|---|---|---|---|
| 16 | Sulphur...... | 34 | 33 97981 | 4.2 | | | |
| | | 35 | | | 87.1 *D* | $e^-$ (0.17) | 54, 55, 194 |
| | | 36 | | 0.016 | | | |
| 17 | Chlorine...... | 33 | 32.9875 | | 2.8 *S* | $e^+$ (4.13) | 49, 56 |
| | | 34 | 33.981 | | 33 *M* | $e^+$ (2.5) | 57, 45, 58 |
| | | 35 | 34 97903 | 75.4 | | | |
| | | 36 | 35.9799 | | $10^6$ *Y* | $e^+$, $e^-$ (0 66) *K* | 59, 2, 194 |
| | | 37 | 36 97786 | 24 6 | | | |
| | | 38 | 37.9800 | | 37 *M* | $e^-$ (1.1, 5 0), (1 65, 2 15) | 60, 26, 61 |
| 18 | Argon | 35 | 34.9865 | | 1 91 *S* | $e^+$ (4.38) | 49, 62 |
| | | 36 | 35 9785 | 0 307 | | | |
| | | 37 | | | 34 *D* | | 63 |
| | | 38 | 37.9751 | 0 061 | | | |
| | | 39 | | | 4 0 *M* | $e^-$ | 51 |
| | | 40 | 39 97564 | 99 632 | | | |
| | | 41 | 40.9770 | | 110 *M* | $e^-$ (1 5), $\gamma$ (1 37) | 28, 30, 64 |
| 19 | Potassium.. | 38 | | | 7 7 *M* | $e^+$ (2.3) $\gamma$ | 58, 64, 51 |
| | | 39 | 38 97518 | 93 4 | | | |
| | | 40 | 39 975 | 0 011 | 4 × $10^8$ *Y* | $e^-$ (0 4, 0 7), $\gamma$ (2 0), *K* | 54, 65 |
| | | 41 | 40 9739 | 6 6 | | | |
| | | 42 | | | 12 4 *H* | $e^-$ (3.5) | 28, 64, 26 |
| | | 43 | | | 18 *M* | $e^-$ | 66 |
| 20 | Calcium . . | 39 | | | 4 5 *M* | $e^+$ | 51, 66 |
| | | 40 | 39 9745 | 96 97 | | | |
| | | 41 | | | 8.5 *D* | $e^-$, $\gamma$ (1 1), *K* | 66 |
| | | 42 | 41 9711 | 0 64 | | | |
| | | 43 | 42.9723 | 0 145 | | | |
| | | 44 | | 2 06 | | | |
| | | 45 | 44.97075 | | 180 *D* | $e^-$ (0 2), $\gamma$ (0.7) | |
| | | 46 | | 0 0033 | | | |
| | | 48 | | 0 185 | | | |
| | | 49 | | | 2 5 *H* | $e^-$ (2 3), $\gamma$ (0 8) | 66 |
| | | 49 | | | 30 *M* | | |
| 21 | Scandium. . | 41 | | | 0.87 *S* | $e^+$ (4 94) | 62, 48 |
| | | 42 | | | 13 5 *D* | $e^+$ (1.4) | 67 |
| | | 43 | | | 4 *H* | $e^+$ (0.4, 1.4), $\gamma$ (1.0) | |
| | | 44 | | | 52 *H* | $e^-$, $\gamma$ (0.268) | 67, 68 |
| | | 44 | | | 41. *H* | $e^+$ (1.45) | 67 |
| | | 45 | 44.96977 | 100 | | | |
| | | 46 | 45.96909 | | 85 *D* | $e^-$ (0.26, 1 25), $\gamma$, *K* | 67 |
| | | 47 | | | 63 *H* | $e^-$ (1.1), $\gamma$ | |

* References are on pp. 291–4.

| Z | *Element Name* | N | *Mass* | % *Abundance* | *Half-Life* | *Radiation* (*Mev*) | *Reference* |
|---|---|---|---|---|---|---|---|
| 21 | Scandium.. | 48 | | | 44 *H* | $e^-$ (0.64), $\gamma$ (1.35) | 67, 51, 69 |
| | | 49 | | | 57 *M* | $e^-$ (1.8) | 67 |
| 22 | Titanium..... | 45 | | | 3 0 *H* | $e^+$ (1.2) | 70 |
| | | 46 | 45 9678 | 7 94 | | | |
| | | 47 | | 7 75 | | | |
| | | 48 | 47 9651 | 73 45 | | | |
| | | 49 | 48 9664 | 5 52 | | | |
| | | 50 | 49 963 | 5 34 | | | |
| | | 51 | | | 2.9 *M* | $e^-$ (0 36), $\gamma$ (1.0) | 67, 26 |
| | | 51 | | | 72 *D* | $e^-$, $\gamma$ | |
| 23 | Vanadium | 47 | | | 600 *D* | *K* | 71 |
| | | 48 | | | 16 *D* | $e^+$ (1.0), $\gamma$ (1.05), *K* | 78, 71 |
| | | 49 | | | 33 *M* | $e^+$ (1 9) | 67, 72 |
| | | 50 | | | 3 7 *H* | $e^+$ | 67 |
| | | 51 | 50.96035 | 100 | | | |
| | | 52 | 51.95857 | | 3 9 *M* | $e^-$ (2.05) | 67, 26, 51 |
| 24 | Chromium | 49 | | | 41 9 *M* | $e^+$ (1.45), $\gamma$ (0.2, 1 6) | 72 |
| | | 50 | | 4 49 | | | |
| | | 51 | | | 26 5 *D* | $e^-$, $\gamma$ (0 5, 1 0), *K* | 66, 73 |
| | | 52 | 51 9582 | 83 78 | | | |
| | | 53 | 52 9572 | 9 43 | | | |
| | | 54 | 53.960 | 2 30 | | | |
| | | 55 | | | 2 *H* | | 73 |
| 25 | Manganese | 51 | | | 46 *M* | $e^+$ (2 0) | 74, 29 |
| | | 52 | | | 21 *M* | $e^+$ (2 2), $\gamma$ (1 2) | 75, 74, 51 |
| | | 52 | | | 6 5 *D* | $e^+$ (0.77), $\gamma$ (1 0) | 74, 75 |
| | | 54 | | | 310 *D* | $\gamma$ (0 845) | 74, 76 |
| | | 55 | 54 965 | 100 | | | |
| | | 56 | | | 2 59 *H* | $e^-$ (0 7, 1.09, 2 88), $\gamma$ (0 846, 1 81, 2.13) | 74, 26, 39 |
| 26 | Iron.. . | 53 | | | 8 9 *M* | $e^+$ | 58, 77 |
| | | 54 | 53.960 | 6 04 | | | |
| | | 55 | | | 4 *Y* | $e^-$, $\gamma$ (0 08), *K* | 60, 77 |
| | | 56 | 55 9572 | 91 54 | | | |
| | | 57 | 56 9609 | 2 11 | | | |
| | | 58 | | 0 28 | | | |
| | | 59 | | | 44 *D* | $e^-$ (0 26, 0 46), $\gamma$ (1.3, 1 1) | 77, 78, 194 |
| 27 | Cobalt . | 55 | | | 18 2 *H* | $e^+$ (1.5), $\gamma$ (0.16, 0.31, 0.8, 1.2) | 74, 79, 51 |
| | | 56 | | | 80 *D* | $e^+$ (1.4), $\gamma$ (0 85, 1 3, 2.6, 3 3) | 74, 39, 80 |

| *Z* | *Element Name* | *N* | *Mass* | % *Abundance* | *Half-Life* | *Radiation* (*Mev*) | *Reference** |
|---|---|---|---|---|---|---|---|
| 27 | Cobalt....... | 57 | | | 270 *D* | $e^+$ (0.26), $\gamma$ (0.12, 0.13), *K* | 74, 81 |
| | | 58 | | | 72 *D* | $e^+$ (0.5), $\gamma$ (0 813), *K* | 74, 76 |
| | | 59 | | 100 | | | |
| | | 60 | | | 5.3 *Y* | $e^-$ (0.31), $\gamma$ (1 1, 1.3) | 74, 76 |
| | | 60 | | | 10.7 *M* | $e^-$ (1.0), $\gamma$ (0.06) | 74, 76 |
| 28 | Nickel........ | 57 | | | 36 *H* | $e^+$ (0 67) | 74 |
| | | 58 | 57.959 | 67.4 | | | |
| | | 59 | | | 15 *Y* | $e^+$ (0.05) | 194 |
| | | 60 | | 26 7 | | | |
| | | 61 | | 1.2 | | | |
| | | 62 | | 3 8 | | | |
| | | 63 | | | 2.6 *H* | $e^-$ (1.9), $\gamma$ (0 28, 0 65, 0.93) | 74, 82 |
| | | 64 | 63 955 | 0 88 | | | |
| 29 | Copper..... | 58 | | | 81 *S* | $e^+$ | 83 |
| | | 60 | | | 7 9 *M* | $e^+$ | 83 |
| | | 61 | | | 3 4 *H* | $e^+$ (0.9), *K* | 58, 83 |
| | | 62 | | | 10.5 *M* | $e^+$ (2.6) | 82, 26 |
| | | 63 | 62 956 | 68 | | | |
| | | 64 | 63 957 | | 12.8 *H* | $e^-$ (0 58, $e^+$ (0.66), *K* | 60, 84, 85 |
| | | 65 | | | 5 *M* | $e^-$ (2.9) | 26, 86 |
| 30 | Zinc..... .. | 63 | | | 38 *M* | $e^+$ (2.32) | 83, 51, 85 |
| | | 64 | 63 956 | 50 9 | | | |
| | | 65 | | | 250 *D* | $e^+$ (0 4), $\gamma$ (1.14), *K* | 74, 41 |
| | | 66 | 65 952 | 27.3 | | | |
| | | 67 | | 3.9 | | | |
| | | 68 | 67 956 | 17.4 | | | |
| | | 69 | | | 13.8 *H* | $\gamma$ (0.44) | 74, 88, 89 |
| | | 69 | | | 47 *M* | $e^-$ (1.0) | 74 |
| | | 70 | 69 954 | 0.5 | | | |
| 31 | Gallium...... | 64 | | | 4.8 *M* | $e^+$ | 90 |
| | | 65 | | | 15 *M* | $\gamma$ (0.054, 0.117), *K* | 91, 74 |
| | | 66 | | | 9.4 *H* | $e^+$ (3.1) | 58, 92 |
| | | 67 | | | 68 *M* | $e^+$ (1.9) | 58, 92, 51 |
| | | 69 | 68 955 | 61.2 | | | |
| | | 70 | | | 19 *M* | $e^-$ (1.7) | 26, 51, 92 |
| | | 71 | 70.953 | 38.8 | | | |
| | | 72 | | | 14 *H* | $e^-$ (2.6), $\gamma$ (1.0) | 69, 52 |
| | | 74 | | | 9 *D* | $e^-$ (0 8) | 87 |

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* References are on pp. 291–4.

| Z | Element Name | N | Mass | % Abundance | Half-Life | Radiation (Mev) | Reference |
|---|---|---|---|---|---|---|---|
| 32 | Germanium | 69 | | | 195 *D* | | 92 |
| | | 70 | | 21 2 | | | |
| | | 71 | | | 40 *H* | $e^{+}$ (1.2) | 94 |
| | | 71 | | | 11 *D* | $\gamma$ ( 6), *K* | 94 |
| | | 72 | | 27 3 | | | |
| | | 73 | | 7 9 | | | |
| | | 74 | | 37 1 | | | |
| | | 75 | | | 89 *M* | $e^{-}$ (1.2) | 94, 52, 87 |
| | | 76 | | 6 5 | | | |
| | | 77 | | | 12 *H* | $e^{-}$ (1.9) | 94, 87, 52 |
| 33 | Arsenic....... | 71 | | | 88 *M* | $e^{+}$ | 60 |
| | | 72 | | | 26 *H* | $e^{+}$ | 60 |
| | | 73 | | | 90 *D* | $\gamma$ (0.052), *K* | 87, 39 |
| | | 73 | | | 50 *H* | $e^{+}$ (0 6) | 87 |
| | | 74 | | | 16 *D* | $e^{-}$ (1.3), $e^{+}$ (0 9), $\gamma$ (0.582) | 95, 96 |
| | | 75 | 74.934 | 100 | | | |
| | | 76 | | | 26 8 *H* | $e^{-}$ (1 1, 1.7, 2.7), $e^{+}$ (0.7, 2.6), $\gamma$, *K* | 97, 95 |
| | | 78 | | | 65 *M* | $e^{-}$ (1.4), $\gamma$ (0.27) | |
| 34 | Selenium... | 74 | | 0 9 | | | |
| | | 75 | | | 125 *D* | $\gamma$ (0.18, 0.35), *K* | 98, 194 |
| | | 76 | | 9 5 | | | |
| | | 77 | | 8 3 | | | |
| | | 78 | 77 938 | 24.0 | | | |
| | | 79 | | | 57 *M* | $\gamma$ (0 099), *I* | 30, 99 |
| | | 80 | 79.942 | 48 0 | | | |
| | | 81 | | | 19 *M* | $e^{-}$ (1 5) | 99 |
| | | 82 | | 9 3 | | | |
| | | 83 | | | 30 *M* | $e^{-}$ | 99 |
| 35 | Bromine ... | 78 | | | 6.4 *M* | $e^{+}$ (2.3), $\gamma$ (0.046, 0 108) | 30, 86, 100 |
| | | 79 | 78 929 | 50 6 | | | |
| | | 80 | | | 4 4 *H* | $\gamma$ (0.49, 0.037), *I* | 51, 100, 30 |
| | | 80 | | | 18 *M* | $e^{-}$ (2.0), $\gamma$ (.5) | |
| | | 81 | 80.930 | 49.4 | | | |
| | | 82 | | | 34 *H* | $e^{-}$ (0.465), (0 55, 0.79, 1 35) | 30, 51, 102 |
| | | 83 | | | 140 *M* | $e^{-}$ (1.05) | 99, 30 |
| | | 84 | | | 30 *M* | $e^{-}$ (4.5) | 103 |
| | | 85 | | | 3.0 *M* | | 103 |
| | | 87 | | | 50 *S* | | 103 |
| 36 | Krypton. . | 78 | 77 945 | 0.35 | | | |
| | | 79 | | | 34 *H* | $e^{+}$ (0.5) | 104 |
| | | 79 | | | | | 104 |

| *Z* | *Element Name* | *N* | *Mass* | % *Abundance* | *Half-Life* | *Radiation (Mev)* | *Reference** |
|---|---|---|---|---|---|---|---|
| 36 | Krypton..... | 80 | | | | | |
| | | 81 | | | | | 104 |
| | | 82 | 81 939 | 11.53 | | | |
| | | 83 | | 11 53 | 113 *M* | $\gamma$ (0.046, 0.029), *I* | 99, 88 |
| | | 84 | 83 938 | 57.11 | | | |
| | | 85 | | | 4 *H* | $e^-$ (0.85) | 105 |
| | | 86 | 85 939 | 17 47 | | | |
| | | 87 | | | 74 *M* | $e^-$ (4 0) | 30 |
| | | 88 | | | 3 *H* | $e^-$ (2.5) | 97 |
| | | 89 | | | 2 5 *M* | | 106 |
| | | 90 | | | 0 5 *M* | | 106 |
| 37 | Rubidium.. | 82 | | | 20 *M* | | 107 |
| | | 84 | | | 6 5 *M* | | 107 |
| | | .. | | | 42 *M* | | 107 |
| | | .. | | | 200 *H* | | 107 |
| | | 85 | | 72 3 | | | |
| | | 86 | | | 19.5 *D* | $e^-$ (1 60) | 30, 108 |
| | | 87 | | 27 7 | $6 \times 10^{10}$ *Y* | $e^-$ (0 13) | 54, 109 |
| | | 88 | | | 18 *M* | $e^-$ (5.1) | 97, 51 |
| | | 89 | | | 15 *M* | $e^-$ (3 8) $\gamma$ | 110 |
| | | 90 | | | 80 *S* | $e^-$ | 106 |
| 38 | Strontium .. | 84 | | 0 56 | | | |
| | | 85 | | | 65 *D* | $\gamma$ (0 8), *K* | 111 |
| | | 85 | | | 70 *M* | $e^-$, $\gamma$ (0.170) | 111 |
| | | 86 | | 9 86 | | | |
| | | 87 | | 7 02 | 2.7 *H* | $e^-$, $\gamma$ (0.386) | 111, 88 |
| | | 88 | | 82 56 | | | |
| | | 89 | | | 55 *D* | $e^-$ (1 32) | 112 |
| | | 90 | | | 7 *M* | $e^-$ | 106 |
| | | 91 | | | 10 *H* | $e^-$ | 106 |
| | | 91 | | | 2 *M* | $e^-$ | 106 |
| 39 | Yttrium.... | 87 | | | 14 *H* | (0 5), *I* | 112, 111 |
| | | 87 | | | 80 *H* | *K* | 111 |
| | | 88 | | | 2 0 *H* | $e^+$ (1 2) | 112 |
| | | 88 | | | 87 *D* | $\gamma$ (0 91, 1 89, 2.8), *K* | 111, 88 |
| | | 89 | | 100 | | | |
| | | 90 | | | 60 *H* | $e^-$ (2.6) | 113 |
| | | 91 | | | 57 *D* | $e^-$ (1.6), $\gamma$ | 106 |
| | | 91 | | | 50 *M* | | 114 |
| 40 | Zirconium... | 89 | | | 78 *H* | $e^+$ (1 0) | 111 |
| | | 89 | | | 4.5 *M* | $\gamma$, *I*, *K* | 111 |
| | | 90 | | 48 | | | |
| | | 91 | | 11.5 | | | |
| | | 92 | | 22 | | | |
| | | 93 | | | 63 *D* | $e^-$ (0.27), $\gamma$ (0.94) | |
| | | 94 | | 17 | | | |

* References are on pp. 291–4.

| *Z* | *Element Name* | *N* | *Mass* | *% Abundance* | *Half-Life* | *Radiation (Mev)* | *Reference* |
|---|---|---|---|---|---|---|---|
| 40 | Zirconium | 95 | | | 17.0 *H* | $e^-$ (1.0) | 116 |
| | | 96 | | 1.5 | | | |
| | | 97 | | | 6 *M* | $e^-$ (1 9) | 115 |
| 41 | Columbium | 92 | | | 11 *D* | $e^-$ (1 38), $\gamma$ (1.0) | 115 |
| | | 93 | 92 926 | 100 | 55 *D* | $\gamma$ (0.15) | 115, 106 |
| | | 94 | | | 6 6 *M* | $e^-$ (1 4), (0.4) | 51, 96 |
| | | 95 | | | 75 *M* | *e* (1 0) | 116 |
| 42 | Molybdenum | 92 | | 14 9 | | | |
| | | 93 | | | 7 *H* | | |
| | | 93 | | | 17 *M* | $e^+$ (2.65) | 115, 51 |
| | | 94 | | 9 4 | | | |
| | | 95 | 94 945 | 16 1 | | | |
| | | 96 | 95 946 | 16 6 | | | |
| | | 97 | 96 945 | 9 65 | | | |
| | | 98 | 97 944 | 24 1 | | | |
| | | 99 | | | 67 *H* | $e^-$ (1 5), $\gamma$ (0 4) | 117 |
| | | 100 | 99 945 | 9 25 | | | |
| | | 101 | | | 17 *M* | $e^-$ (1 8),<br>$\gamma$ (0 3, 0 6) | 115 |
| 43 | —— | 96 | | | 2 7 *H* | $e^+$ | 83, 117 |
| | | 99 | | | 6 6 *H* | $\gamma$ (0 136), *I* | 117, 106 |
| | | 101 | | | 12 *M* | $e^-$ (1 1), $\gamma$ (0.3) | 118 |
| | | | | | 90 *D* | $\gamma$ (0 097), *K* | 119 |
| | | | | | 62 *D* | $\gamma$, *K* | 119 |
| | | | | | 110 *H* | $\gamma$ (0 05, 0.5), *K* | 120 |
| | | | | | 55 *H* | $e^-$ (2 5) | 120 |
| 44 | Ruthenium | 95 | | | 20 *M* | | 51, 121 |
| | | 96 | 95 946 | 5 68 | | | |
| | | 98 | | 2 22 | | | |
| | | 99 | 98 944 | 12 91 | | | |
| | | 100 | | 12 70 | | | |
| | | 101 | | 16 98 | | | |
| | | 102 | | 31 34 | | | |
| | | 104 | | 18 27 | | | |
| | | 105 | | | 4 *H* | $e^-$ (1 5) | 121, 122 |
| | | | | | 45 *D* | | 122 |
| | | | | | 4 *M* | $e^-$ (4.0) | 123 |
| 45 | Rhodium | 101 | | 0 08 | | | |
| | | 102 | | | 210 *D* | $e^-$ (1.1), $e^+$ | 124 |
| | | 103 | | 99 92 | | | |
| | | 104 | | | 4.2 *M* | $\gamma$ (0.055, 0.080), *I* | 51, 26, 125 |
| | | 104 | | | 44 *S* | $e^-$ (2.3) | 125, 26 |
| | | 105 | | | 34 *H* | $e^-$ (0.5) | 122 |
| | | ... | | | 24 *M* | $e^-$ (1.2) | 123 |

| Z | Element Name | N | Mass | % Abundance | Half-Life | Radiation (Mev) | Reference* |
|---|---|---|---|---|---|---|---|
| 46 | Palladium | 102 | | 0.8 | | | |
| | | 104 | 103.946 | 9.3 | | | |
| | | 105 | 104.945 | 22.6 | | | |
| | | 106 | 105.945 | 27.2 | | | |
| | | 107 | | | 13 *H* | $e^-$ (1.03) | 126 |
| | | 108 | 107.943 | 26.8 | | | |
| | | 110 | 109.942 | 13.5 | | | |
| | | 111 | | | 26 *M* | $e^-$ (3.5) | 123, 26 |
| | | 112 | | | 17 *H* | $e^-$ | 122 |
| 47 | Silver | 102 | | | 73 *M* | $e^+$ | 127 |
| | | 104 | | | 16.3 *M* | $e^+$ | 127 |
| | | 105 | | | 45 *D* | $\gamma$ (0.29, 0.42, 0.50, 0.62), *K* | 127 |
| | | 106 | | | 24.5 *M* | $e^+$ (2.04) | 29, 128 |
| | | 106 | | | 8.2 *D* | $\gamma$ (1.06, 0.69), *K* | 128, 126 |
| | | 107 | 106.948 | 51.9 | 40 *S* | $\gamma$ (0.093) | 129 |
| | | 108 | 107.947 | | 2.3 *M* | $e^-$ (2.8) | 26, 130, 51 |
| | | 109 | | 48.1 | | | |
| | | 110 | | | 22 *S* | $e^-$ (2.8) | 26, 128 |
| | | 110 | | | 225 *D* | $\gamma$ (0.65, 0.92, 1.51), *K* | 74, 131 |
| | | 111 | | | 7.5 *D* | $e^-$ (0.8) | 126, 128 |
| | | 112 | | | 3.2 *H* | $e^-$ (2.2) | 128 |
| 48 | Cadmium | 106 | | 1.4 | | | |
| | | 107 | | | 6.7 *H* | $\gamma$ (0.53), *K* | 83 |
| | | 107 | | | 158 *D* | *K* | 88 |
| | | 108 | | 1.0 | | | |
| | | 109 | | | 33 *M* | $e^+$ | 51 |
| | | 110 | | 12.8 | | | |
| | | 111 | | 13.0 | | | |
| | | 112 | | 24.2 | | | |
| | | 113 | | 12.3 | | | |
| | | 114 | | 28.0 | | | |
| | | 115 | | | 2.5 *D* | $e^-$ (1.11), $\gamma$ (0.65) | 132 |
| | | 115 | | | 43 *D* | $e^-$ (1.5) | 194 |
| | | 116 | | 7.3 | | | |
| | | 117 | | | 3.75 *H* | $e^-$ | 132 |
| | | ... | | | 48.7 *M* | $\gamma$ (0.195), *I* | 133 |
| 49 | Indium | 110 | | | 65 *M* | $e^+$ (1.6) | 134 |
| | | 111 | | | 20 *M* | $e^+$ (1.7), $\gamma$ (0.16) | 134 |
| | | 112 | | | 2.7 *D* | $\gamma$ (0.17, 0.25), *K* | 132, 134 |
| | | 112 | | | 16.5 *M* | $\gamma$ (0.12), *I* | 135 |
| | | 112 | | | 17.5 *M* | $e^+$ (1.3), $\gamma$ (0.095) | 135 |
| | | 113 | | 4.5 | 105 *M* | $\gamma$ (0.39), *I* | 134 |
| | | 114 | | | 48 *D* | $\gamma$ (0.19), *I* | 134, 136 |
| | | 114 | | | 72 *S* | $e^-$ (1.98) | 136, 86 |

* References are on pp. 291–4.

| *Z* | *Element Name* | *N* | *Mass* | % *Abundance* | *Half-Life* | *Radiation* (*Mev*) | *Reference* |
|---|---|---|---|---|---|---|---|
| 49 | Indium ..... | 115 | | 95.5 | 4.1 *H* | $\gamma$ (0.34), *I* | 136, 137 |
| | | 116 | | | 13 *S* | $e^-$ (2.8) | 26, 132 |
| | | 116 | | | 54 *M* | $e^-$ (0.85), $\gamma$ (2.3, 1.3, 1.1, 0.43) | 26, 136 |
| | | 117 | | | 117 *M* | $e^-$ (1.73), $\gamma$ | 136, 132 |
| 50 | Tin.......... | 112 | | 1.1 | | | |
| | | 113 | | | 90 *D* | $\gamma$ (0.085), *K* | 74, 134 |
| | | 114 | | 0.8 | | | |
| | | 115 | | 0.4 | | | |
| | | 116 | 115.942 | 15.5 | | | |
| | | 117 | | 9.1 | | | |
| | | 118 | 117.939 | 22.5 | | | |
| | | 119 | 118.938 | 9.8 | | | |
| | | 120 | 119.940 | 28.5 | | | |
| | | 122 | 121.944 | 5.5 | | | |
| | | 124 | 123.943 | 6.8 | | | |
| | | 125 | | | 9 *M* | $e^-$ | 74 |
| | | .. | | | 40 *M* | $e^-$ | 74 |
| | | . | | | 26 *H* | $e^-$ | 74 |
| | | .. | | | 10 *D* | $e^-$ | 74 |
| | | | | | 400 *D* | $e^-$ | 74 |
| 51 | Antimony.... | 118 | | | 3.6 *M* | $e^+$ | 111 |
| | | 120 | | | 17 *M* | $e^+$ (1.53) | 51, 74 |
| | | 121 | | 56 | | | |
| | | 122 | | | 2.8 *D* | $e^-$ (0.81, 1.64), $\gamma$ (0.80) | 74, 26 |
| | | 123 | | 44 | | | |
| | | 124 | | | 60 *D* | $e^-$ (0.74, 2.45), $\gamma$ (1.8) | 74, 138 |
| | | 126 | | | 3 *H* | $e^-$ | 74 |
| | | 127 | | | 80 *H* | $e^-$ | 139 |
| | | 129 | | | 4.2 *H* | $e^-$ | 139 |
| | | 131 | | | 5 *M* | $e^-$ | 139 |
| | | 133 | | | 10 *M* | $e^-$ | 139 |
| 52 | Tellurium.... | 120 | | 0.1 | | | |
| | | 121 | | | 125 *D* | *K* | 140 |
| | | 122 | | 2.9 | 30 *D* | (0.082, 0.088, 0.136, 0.157) *I* | 141 |
| | | 123 | | 1.6 | | | |
| | | 124 | | 4.5 | | | |
| | | 125 | | 6.0 | | | |
| | | 126 | 125.937 | 19.0 | | | |
| | | 127 | | | 90 *D* | $\gamma$ (0.086), *I* | 140 |
| | | 127 | | | 9.3 *H* | $e^-$ | 140, 142 |
| | | 128 | 127.936 | 32.8 | | | |
| | | 129 | | | 32 *D* | $\gamma$ (0.102) *I* | 140, 142 |
| | | 129 | | | 72 *M* | $e^-$ | 140, 130, 139 |
| | | 130 | | 33.1 | | | |

| Z | Element Name | N | Mass | % Abundance | Half-Life | Radiation (Mev) | Reference* |
|---|---|---|---|---|---|---|---|
| 52 | Tellurium.... | 131 | | | 30 *H* | $\gamma$ (0.177), *I* | 140, 139 |
| | | 131 | | | 25 *M* | $e^-$ | 140, 139 |
| | | 133 | | | 60 *M* | $e^-$ | 139, 143 |
| | | 135 | | | 15 *M* | $e^-$ | 143 |
| 53 | Iodine..... | 124 | | | 4.0 *D* | $e^+$ | 77 |
| | | 126 | | | 13.0 *D* | $e^-$ (1.1), $\gamma$ (0.5) | 77, 142 |
| | | 127 | 126.933 | 100 | | | |
| | | 128 | | | 25.0 *M* | $e^-$ (1.85), $\gamma$ (0.4) | 26, 142 |
| | | 130 | | | 12.6 *H* | $e^-$ (0.61, 1.03),<br>$\gamma$ (0.42, 0.54) | 77, 143, 131 |
| | | 131 | | | 8.0 *D* | $e^-$ (0.69),<br>(0.08, 0.37) | 77, 144, 139 |
| | | 133 | | | 22 *H* | $e^-$ (1.1) | 139, 143, 106 |
| | | 135 | | | 6.6 *H* | $e^-$ | 143 |
| | | 137 | | | 30 *S* | | 103 |
| 54 | Xenon...... | 124 | | 0.094 | | | |
| | | 126 | | 0.088 | | | |
| | | 127 | | | 75 *S* | $\gamma$ (0.175, 0.125), *I* | 104 |
| | | 127 | | | 34 *D* | $\gamma$ (0.9) | 104 |
| | | 128 | | 1.90 | | | |
| | | 129 | 128.946 | 26.23 | | | |
| | | 130 | | 4.07 | | | |
| | | 131 | | 21.17 | | | |
| | | 132 | 131.946 | 26.96 | | | |
| | | 133 | | | 6.3 *D* | $\gamma$ (0.083) | 123, 143 |
| | | 134 | | 10.54 | | | |
| | | 135 | | | 9.4 *H* | $e^-$ (0.9) | 143, 123 |
| | | 135 | | | 15.6 *M* | $e^-$ (0.65), $\gamma$ | 114, 123 |
| | | 136 | | 8.95 | | | |
| | | 137 | | | 68 *M* | | 105 |
| | | 137 | | | 3.4 *M* | $e^-$ (4.0) | 123, 145 |
| | | 138 | | | 17 *M* | $e^-$ | 110, 106 |
| | | 139 | | | 30 *S* | $e^-$ | 106 |
| 55 | Caesium . | 133 | | 100 | | | |
| | | 134 | | | 3 *H* | $e^-$ (1.0) | 26, 146 |
| | | 134 | | | 2.0 *Y* | $e^-$ (0.75), $\gamma$ (0.8) | 146, 194 |
| | | 138 | | | 33 *M* | $e^-$ (2.6) | 106, 110 |
| | | 139 | | | 7 *M* | $e^-$ | 106 |
| | | 140 | | | 40 *S* | $e^-$ | 106 |
| 56 | Barium...... | 130 | | 0.10 | | | |
| | | 132 | | 0.09 | | | |
| | | 133 | | | 38.8 *H* | (0.276), *I* | 147, 148 |
| | | 134 | | 2.42 | | | |
| | | 135 | | 6.59 | | | |
| | | 136 | | 7.81 | | | |
| | | 137 | | 11.32 | | | |
| | | 138 | 137.916 | 71.66 | | | |

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* References are on pp. 291–4.

| *Z* | *Element Name* | *N* | *Mass* | % *Abundance* | *Half-Life* | *Radiation (Mev)* | *Reference* |
|---|---|---|---|---|---|---|---|
| 56 | Barium..... | 139 | | | 86 *M* | $e^-$ (1.0, 2.3), $\gamma$ (0.6) | 106, 26, 51 |
| | | 140 | | | 300 *H* | $e^-$ (1 2) | 106, 123, 110 |
| | | 142 | | | 18 *M* | $e^-$ | 149 |
| 57 | Lanthanum.. | 137 | | | 17.5 *H* | $\gamma$ (0 88), *K* | 148 |
| | | 138 | | | 2.2 *H* | | 51 |
| | | 139 | 138 955 | 100 | | | |
| | | 140 | | | 40 0 *H* | $e^-$ (1.41), (2.04) | 148, 149 |
| | | >140 | | | 74 *M* | $e^-$ | 106 |
| | | >140 | | | 3 5 *H* | $e^-$ | 106, 150 |
| | | >140 | | | 15 *M* | $e^-$ | 106 |
| | | >140 | | | 13 *D* | $e^-$ | 106 |
| 58 | Cerium .. | 136 | | 0 002 | | | |
| | | 138 | | 0 002 | | | |
| | | 139 | | | 2 1 *M* | $e^+$ | 151 |
| | | 140 | | 90.0 | 140 *D* | $\gamma$ (0 21), *I* | 151 |
| | | 141 | | | 28 *D* | $e^-$ (0 60),<br>$\gamma$ (0.22) | 151 |
| | | 142 | | 10 0 | | | |
| | | 143 | | | 33 *H* | $e^-$ (1 36), $\gamma$ (0 5) | 151 |
| | | 143 | | | 15 *D* | $e^-$ (0.12) | 18 |
| | | >143 | | | 310 *D* | $e^-$ | 123 |
| | | >143 | | | 20 *D* | $e^-$ | 106 |
| | | >143 | | | 40 *H* | $e^-$ | 106 |
| 59 | Praseodymium | 140 | | | 3 5 *M* | $e^+$ (2 40) | 151, 26 |
| | | 141 | | 100 | | | |
| | | 142 | | | 19.3 *H* | $e^-$ (2 14), $\gamma$ (1 9) | 51, 152, 26 |
| | | 143 | | | 13.5 *D* | $e^-$ (0.95) | 151 |
| | | >143 | | | 17 *M* | $e^-$ (3.1) | 106 |
| 60 | Neodymium | 141 | | | 2 5 *H* | $e^+$ (0 78) | 151 |
| | | 142 | | 25 95 | | | |
| | | 143 | | 13 0 | | | |
| | | 144 | | 22 6 | | | |
| | | 145 | | 9 2 | | | |
| | | 146 | 145 960 | 16 5 | | | |
| | | 147 | | | 47 *H* | $e^-$ (0.95) | 143, 151 |
| | | 148 | 147 961 | 6 8 | | | |
| | | 150 | 149 967 | 5.95 | | | |
| | | 151 | | | 21 *M* | $e^-$ | 151 |
| 61 | —— | ... | | | 12 5 *H* | $e^-$ | 151 |
| | | . | | | 200 *D* | $e^-$ | 143 |
| | | ... | | | 2 7 *H* | $e^-$ | 152 |
| | | . . | | | 16 *D* | $e^-$ | 152 |
| 62 | Samarium.... | 144 | | 3 | | | |
| | | 147 | | 17 | | | |
| | | 148 | | 14 | $1.6 \times 10^{11}$ *Y* | $\gamma$ (2.0) | 153 |

| Z | Element Name | N | Mass | % Abundance | Half-Life | Radiation (Mev) | Reference* |
|---|---|---|---|---|---|---|---|
| 62 | Samarium.... | 149 | | 15 | | | |
| | | 150 | | 5 | | | |
| | | 152 | | 26 | | | |
| | | 154 | | 20 | | | |
| | | >154 | | | 21 *M* | $e^-$ (1.8) | 151, 152, 26 |
| | | >154 | | | 46 *M* | (0.6), *I* | 143, 151, 152 |
| | | >154 | | | 60 *D* | | 152 |
| 63 | Europium... | 150 | | | 27 *H* | $e^+$ | 151, 18 |
| | | 151 | | 49.1 | | | |
| | | 152 | | | | | |
| | | 153 | | 50 9 | | | |
| | | 154 | | | 6 *Y* | $e^-$ (0.9), $\gamma$ | 18, 154 |
| | | >154 | | | 40 *D* | | 152 |
| 64 | Gadolinium.. | 152 | | 0 2 | | | |
| | | 154 | | 2 86 | | | |
| | | 155 | 154 977 | 15 61 | | | |
| | | 156 | 155 976 | 20 59 | | | |
| | | 157 | | 16.42 | | | |
| | | 158 | | 23.45 | | | |
| | | 159 | | | 8 *H* | | 26, 155 |
| | | 160 | | 20 87 | | | |
| | | >160 | | | 162 *D* | $e^-$, $\gamma$ | 154 |
| 65 | Terbium .... | 159 | | 100 | | | |
| | | 160 | | | 3 9 *H* | $e^-$ | 155, 151 |
| | | 160 | | | 72 *D* | $e^-$ (0.70), $\gamma$ | 156 |
| 66 | Dysprosium . | 158 | | 0 1 | | | |
| | | 160 | | 1 5 | | | |
| | | 161 | | 22 | | | |
| | | 162 | | 24 | | | |
| | | 163 | | 24 | | | |
| | | 164 | | 28 | | | |
| | | 165 | | | 2.5 *H* | $e^-$ (1.18), $\gamma$ (1.1) | 155, 151 |
| 67 | Holmium..... | 164 | | | 47 *M* | $e^-$ | 151 |
| | | 165 | 164 98 | 100 | | | |
| | | 166 | | | 35 *H* | $e^-$ (1 7) | 155, 151 |
| 68 | Erbium...... | 162 | | 0.1 | | | |
| | | 164 | | 1.5 | | | |
| | | 165 | | | 1.1 *M* | $e^+$ | 151 |
| | | 166 | | 32 9 | | | |
| | | 167 | | 24 4 | | | |
| | | 168 | | 26 9 | | | |
| | | 169 | | | 7 *M* | | 157 |
| | | 170 | | 14.2 | | | |
| | | 171 | | | 12 *H* | $e^-$ | 155, 151 |

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* References are on pp. 291–4.

| Z | Element Name | N | Mass | % Abundance | Half-Life | Radiation (Mev) | Reference |
|---|---|---|---|---|---|---|---|
| 69 | Thulium.... | 169 | | 100 | | | |
| | | 170 | | | 105 *D* | | 155 |
| 70 | Ytterbium... | 168 | | 0 06 | | | |
| | | 170 | | 4 21 | | | |
| | | 171 | | 14 26 | | | |
| | | 172 | | 21 49 | | | |
| | | 173 | | 17 02 | | | |
| | | 174 | | 29 58 | | | |
| | | 175 | | | 3.5 *H* | | 155, 151, 157 |
| | | 176 | | 13 38 | | | |
| 71 | Lutecium .. | 175 | | 97 5 | | | |
| | | 176 | | 2 5 | $7.3 \times 10^{10}$ *Y* | $e^-$ (0.40), $\gamma$ (0.26) | 158 |
| | | 176 | | | 3.4 *H* | $e^-$ (1.15) | 159 |
| | | 177 | | | 6.6 *D* | $e^-$ (0.44) | 159, 155 |
| 72 | Hafnium . | 174 | | 0 18 | | | |
| | | 176 | | 5 30 | | | |
| | | 177 | | 18 47 | | | |
| | | 178 | | 27 13 | | | |
| | | 179 | | 13 85 | | | |
| | | 180 | | 35 14 | | | |
| | | 181 | | | 55 *D* | $e^-$ | 155 |
| 73 | Tantalum . | 180 | | | 17 *M* | | 160 |
| | | 180 | | | 8.2 *H* | $\gamma$, *K* | 161 |
| | | 181 | 180 928 | 100 | | | |
| | | 182 | | | 97 *D* | $e^-$ (0.53),<br>$\gamma$ (1.22, 1.13) | 161, 162, 194 |
| 74 | Tungsten . | 180 | | 0 2 | | | |
| | | 182 | | 22 6 | | | |
| | | 183 | | 17 3 | | | |
| | | 184 | 184 00 | 30 1 | | | |
| | | 185 | | | 77 *D* | $e^-$ (0 67), $\gamma$ | 163 |
| | | 186 | | 29 8 | | | |
| | | 187 | | | 24.1 *H* | $e^-$ (1 4), $\gamma$ (0 14, 0 10, 0.086) | 163, 101 |
| 75 | Rhenium..... | >184 | | | 40 *M* | $e^+$ | 164 |
| | | >184 | | | 13 *M* | | 164 |
| | | 184 | | | 52 *D* | $\gamma$ (0.85), *K* | 163, 164 |
| | | 185 | | 38 2 | | | |
| | | 186 | | | 90 *H* | $e^-$ (1.05) | 164 |
| | | 187 | 186 981 | 61 8 | | | |
| | | 188 | | | 18 *H* | $e^-$ (2 5), $\gamma$ (0 8) | |
| 76 | Osmium..... | 184 | | 0 018 | | | |
| | | 186 | | 1 59 | | | |
| | | 187 | | 1 64 | | | |

| Z | *Element Name* | *N* | *Mass* | % *Abundance* | *Half-Life* | *Radiation (Mev)* | *Reference** |
|---|---|---|---|---|---|---|---|
| 76 | Osmium...... | 188 | | 13 3 | | | |
| | | 189 | | 16 1 | | | |
| | | 190 | 190 038 | 26.4 | | | |
| | | 191 | | | 32 *H* | $e^-$ (1.5), $\gamma$ | 165 |
| | | 192 | 192 038 | 41 0 | | | |
| | | 193 | | | 17 *D* | $e^-$ (0 35), $\gamma$ | 165 |
| 77 | Iridium.. .. | 191 | 191 040 | 38 5 | | | |
| | | 192 | | | 1 5 *M* | $e^-$ | 166 |
| | | 192 | | | 19 *H* | $e^-$ (2.18), $\gamma$ (1.35) | 26, 51, 167 |
| | | 193 | 193 041 | 61 5 | | | |
| | | 194 | | | 60 *D* | $e^-$, $\gamma$ (0 31, 0 47, 0 60) | 166 |
| 78 | Platinum ... | 192 | | 0 8 | | | |
| | | 194 | 194 040 | 30 2 | | | |
| | | 195 | 195 040 | 35 3 | | | |
| | | 196 | 196 039 | 26 6 | 80 *M* | $\gamma$, *I* | 169 |
| | | 197 | | | 18 *H* | $e^-$ (0 68) | 168, 166, 169 |
| | | 197 | | | 3 3 *D* | $e^-$, $\gamma$ | 166, 51 |
| | | 198 | 198 044 | 7.2 | | | |
| | | 199 | | | 31 *M* | $e^-$ (1 8) | 166, 168, 169 |
| 79 | Gold.... .. | 196 | | | 13 *H* | $e^-$ | 166 |
| | | 196 | | | 5 *D* | $e^-$ (0 36), $\gamma$ (0 356) | 136, 166 |
| | | 197 | 197 039 | 100 | | | |
| | | 198 | | | 2.7 *D* | $e^-$ (0.78), $\gamma$ (0.28, 0.44, 2.5) | 26, 51, 166, 167 |
| | | 199 | | | 3 3 *D* | $e^-$ (1 01), $\gamma$ (0 33, 0 41) | 166, 193 |
| | | 200 | | | 48 *M* | $e^-$ (2.5) | 161, 118 |
| 80 | Mercury...... | 196 | | 0.15 | | | |
| | | 197 | | | 23 *H* | $\gamma$ (0.13, 0.16), *K* | 171 |
| | | 197 | | | 64 *H* | $\gamma$ (0 75), *K* | 171 |
| | | 198 | | 10 1 | | | |
| | | 199 | | 17 0 | 43 *M* | $\gamma$ (0.53), *I* | 166, 51, 169 |
| | | 200 | 200 028 | 23 3 | | | |
| | | 201 | | 13 2 | | | |
| | | 202 | | 29 6 | | | |
| | | 203 | | | 51.5 *D* | $e^-$ (0.30), $\gamma$ (0 28) | 171, 169 |
| | | 204 | | 6 7 | | | |
| | | 205 | | | 5 5 *M* | $e^-$ (1 62) | 172, 118 |
| 81 | Thallium.. | 200 | | | 4 *M* | | 173 |
| | | 200 | | | 3 8 *H* | | 173 |
| | | 202 | | | 12 4 *D* | $\gamma$ (0.40), *K* | 118, 172 |
| | | 203 | 203 057 | 29 1 | | | |
| | | 204 | | | 4 23 *M* | $e^-$ (1.68) | 51, 154 |

* References are on pp 291–4.

| *Z* | *Element Name* | *N* | *Mass* | *% Abundance* | *Half-Life* | *Radiation (Mev)* | *Reference* |
|---|---|---|---|---|---|---|---|
| 81 | **Thallium** . . . | 205 | 205 057 | 70 9 | | | |
| | | 206 | | | 3.5 *Y* | $e^-$ (0.87) | 154 |
| | (Ac C″) | 207 | | | 4 76 *M* | $e^-$ (1 47), $\gamma$ | 174, 175 |
| | (Th C″) | 208 | | | 3 1 *M* | $e^-$ (1 82), $\gamma$ (2 62) | 174, 175 |
| | (Ra C″) | 210 | | | 1.32 *M* | $e^-$ (1.80) | 175 |
| 82 | **Lead**. . . . . . . . | 203 | | | 10 25 *M* | $e^+$ (1 66) | 172 |
| | | 203 | | | 52 *H* | $\gamma$ (0 27), *I* | 154, 172 |
| | | 204 | 204 058 | 1 5 | 68 *M* | $\gamma$ (0 90), *I* | 118, 154 |
| | | 205 | | | 51 5 *D* | $e^-$(0.3), $\gamma$ (0.28) | 194 |
| | | 206 | | 23 6 | | | |
| | | 207 | | 22 6 | | | |
| | | 208 | 208.057 | 52.3 | | | |
| | | 209 | | | 3.0 *H* | $e^-$ (0.72) | 154, 172 |
| | (Ra D) | 210 | | | 22 *Y* | $e^-$ (0.025), $\gamma$ (0 047) | 175 |
| | (Ac B) | 211 | | | 36.1 *M* | $e^-$ (0.5, 1.4), $\gamma$ (0 8) | 174 |
| | (Th B) | 212 | | | 10 6 *H* | $e^-$ (0.36), $\gamma$ | 175 |
| | (Ra B) | 214 | | | 26 8 *M* | $e^-$ (0 65), $\gamma$ | 175, 174 |
| 83 | **Bismuth** . | 207 | | | 6.4 *D* | $\gamma$ (0 93), *K* | 172, 154 |
| | | 209 | 209.055 | 100 | | | |
| | (Ra E) | 210 | | | 5 0 *D* | $e^-$ (1.17) | 115 |
| | (Ac C) | 211 | | | 2 16 *M* | $\alpha$ (6 619), $e^-$ $\gamma$ | 175 |
| | (Th C) | 212 | | | 60 5 *M* | $\alpha$ (6.054), $e^-$ (2 20), $\gamma$ | 175 |
| | (Ra C) | 214 | | | 19.7 *M* | $\alpha$ (5.502),<br>$e^-$ (3.15), $\gamma$ (1.8) | 175<br>175 |
| 84 | **Polonium** | 210 | | | 140 *D* | $\alpha$ (5 298), $\gamma$ | 175, 170 |
| | (Ac C′) | 211 | | | $5 \times 10^{-3}$ *S* | $\alpha$ (7.434) | 175 |
| | (Th C′) | 212 | | | $3 \times 10^{-7}$ *S* | $\alpha$ (8 776) | 176 |
| | (Ra C′) | 214 | | | $1.5 \times 10^{-4}$ *S* | $\alpha$ (7 68) | 176 |
| | (Ac A) | 215 | | | $1\ 83 \times 10^{-3}$ *S* | $\alpha$ (7.365) | 177 |
| | (Th A) | 216 | | | $1.58 \times 10^{-1}$ *S* | $\alpha$ (6 774), $e^-$ | 177 |
| | (Ra A) | 218 | | | 3 05 *M* | $\alpha$ (5 998) | 175 |
| 85 | —— | 211 | | | 7.5 *H* | $\alpha$ (5 94), $\gamma$, *K* | 178 |
| | | 216 | | | 50 *S* | $\alpha$ (7.64) | 179 |
| | | 218 | | | 710 *S* | $\alpha$ (6 63) | 179 |
| 86 | **Radon** | | | | | | |
| | (An) | 219 | | | 3 92 *S* | $\alpha$ (6 824) | 175 |
| | (Tn) | 220 | | | 54.5 *S* | $\alpha$ (6 282) | 180, 175 |
| | (Rn) | 222 | | | 3 825 *D* | $\alpha$ (5 486) | 175, 180 |
| 87 | —— | 223 | | | 21 *M* | $e^-$ (1 20), $\gamma$ (3) | 181 |
| 88 | **Radium** | | | | | | |
| | (Ac x) | 223 | | | 11 2 *D* | $\alpha$ (6 717), $\gamma$ | 175 |
| | (Th x) | 224 | | | 3.64 *D* | $\alpha$ (5.681) | 182 |
| | | 226 | 226.10 | | 1590 *Y* | $\alpha$ (4.791), $\gamma$ (0.19) | 175 |
| | (Ms $Th_I$) | 228 | | | 6 7 *Y* | $e^-$ (0 053) | 175 |

| Z | *Element Name* | *N* | *Mass* | % *Abundance* | *Half-Life* | *Radiation (Mev)* | *Reference** |
|---|---|---|---|---|---|---|---|
| 89 | Actinium..... | 227 | | | 13.5 *Y* | $\alpha$ (5.0), $e^-$ (0.22) | 175, 181 |
| | (Ms $Th_2$) | 228 | | | 6.13 *H* | $\alpha$ (4.5), $e^-$ (1.55), $\gamma$ | 175, 54 |
| 90 | Thorium | | | | | | |
| | (Rd Ac) | 227 | | | 18.9 *D* | $\alpha$ (6.049), $\gamma$ | 175, 183 |
| | (Rd Th) | 228 | | | 1.9 *Y* | $\alpha$ (5.418), $\gamma$ | 175, 183 |
| | | 229 | | | $5 \times 10^3$ *Y* | $\alpha$ (5.0) | 191 |
| | (IO) | 230 | | | $8.3 \times 10^4$ *Y* | $\alpha$ (4 66), $\gamma$ | 175 |
| | (UY) | 231 | | | 24.6 *H* | $e^-$ | 175 |
| | | 232 | 232.12 | 100 | $1.3 \times 10^{10}$ *Y* | $\alpha$ (3.97) | 184 |
| | | 233 | | | 23.5 *M* | $e^-$ | 185 |
| | ($UX_1$) | 234 | | | 24.5 *D* | $e^-$ (0.12, 0.30), $\gamma$ (0 092) | 174, 175 |
| 91 | Protactinium . | 231 | | | $3.2 \times 10^4$ *Y* | $\alpha$ (5.05), $\gamma$ | 186 |
| | | 232 | | | 1.6 *D* | $e^-$ $\gamma$ | 191 |
| | | 233 | | | 27.4 *D* | $e^-$ (0.23), $\gamma$ (0 06, 0 19, 0.28) | 185 |
| | (UZ) | 234 | | | 6.7 *H* | $e^-$ (0 56, 1.55), $\gamma$ (0 70) | 175 |
| | ($UX_2$) | 234 | | | 1.14 *M* | $e^-$ (2 32), $\gamma$ (0.802) | 175 |
| 92 | Uranium.... | 232 | | | 30 *Y* | $\alpha$ (5.31) | 191 |
| | | 233 | | | $1.63 \times 10^5$ *Y* | $\alpha$ (4.83), $e^-$, $\gamma$, *K* | 191 |
| | | 234 | | 0 006 | $2.5 \times 10^5$ *Y* | $\alpha$ (4 76) | 187 |
| | | 235 | 235.12 | 0 71 | $8.8 \times 10^8$ *Y* | $\alpha$ (4.52) | 187 |
| | | 237 | | | 6.9 *D* | $e^-$ (0.26), $\gamma$ (0 5) | 188 |
| | | 238 | 238 14 | 99 28 | $4.51 \times 10^9$ *Y* | (4.18) | 187 |
| | | 239 | | | 23.5 *M* | $e^-$ (0 56, 1.2), $\gamma$ (0.076) | 189 |
| 93 | Neptunium.. | 235 | | | >1 *Y* | $\gamma$, *K* | 191 |
| | | 237 | | | $2.2 \times 10^6$ *Y* | $\alpha$ (4.77) | 191 |
| | | 238 | | | 2.0 *D* | $e^-$ (1.35), $\gamma$ (0.1, 0 25, 1.3) | 11 |
| | | 239 | | | 2.33 *D* | $e^-$ (0.14, 0 78), $\gamma$ (0.22, 0.27) | 190 |
| 94 | Plutonium.... | 236 | | | ..... | $\alpha$ (5.75) | 191 |
| | | 237 | | | .... | *K* | 191 |
| | | 238 | | | 60 *Y* | $\alpha$ (5 52) | 11 |
| | | 239 | | | $2.4 \times 10^4$ *Y* | $\alpha$ (5.16), $\gamma$ (0.3) | 11 |
| | | 241 | | | | $\alpha$, $e^-$ | 191 |
| 95 | Americium.... | 241 | | | 50 *Y* | $\alpha$ (5.47) | 191 |
| 96 | Curium...... | 241 | | | 30 *D* | $\alpha$ (6 25) | 191 |
| | | 242 | | | 0.7 *Y* | $\alpha$ (6 0) | 191 |

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* References are on pp. 291–4.

# REFERENCES

1. L. Alvarez and R. Cornog, *Phys. Rev.*, **56**, 613 (1939); **58**, 197 (1940).
2. R. O'Neal and M. Goldhaber, *Phys. Rev.*, **57**, 1086 (1940); **58**, 574 (1940); **60**, 359 (1941).
3. T. Bjerge and K. Brostrom, *Nature*, **138**, 400 (1936); *Dansk. Math. Phys. Medd.*, **16**, 8 (1938).
4. M. Nahmias and R. Walen, *Comptes Rendus*, **203**, 71 (1936).
5. K. Knol and J. Veldkamf, *Physics*, **3**, 145 (1936).
6. H. Crane, L. Delsasso, W. Fowler, and C. Lauritsen, *Phys. Rev.*, **47**, 887, 971 (1935).
7. D. Bayley and H. Crane, *Phys. Rev.*, **52**, 604 (1937).
8. L. Rumbaugh and L. Hafstad, *Phys. Rev.*, **50**, 681 (1936).
9. R. Roberts, N. Heydenburg, and G. Locher, *Phys. Rev.*, **53**, 1016 (1938).
10. L. Rumbaugh, R. Roberts, and L. Hafstad, *Phys. Rev.*, **54**, 657 (1938).
11. The Smyth Report, Princeton Press (1945).
12. E. Hill and G. Valley, *Phys. Rev.*, **55**, 678 (1939); **57**, 567 (1940).
13. E. McMillan, *Rev. Mod. Phys.*, **16**, 3 (1944).
14. R. Becker and E. Gaerttner, *Phys. Rev.*, **56**, 854 (1939).
15. W. Barkas, E. Creutz, L. Delsasso, J. Fox, and M. White, *Phys. Rev.*, **57**, 562 (1940); **58**, 586 (1940).
16. H. Crane and C. Lauritsen, *Phys. Rev.*, **45**, 497 (1934).
17. J. Solomon, *Phys. Rev.*, **60**, 279 (1941).
18. S. Ruben and M. Kamen, *Phys. Rev.*, **57**, 489, 549 (1940); **59**, 349 (1941).
19. J. Cockcroft, C. Gilbert, and E. Walton, *Proc. Roy. Soc.*, **148**, 225 (1935).
20. L. Hafstad and M. Tuve, *Phys. Rev.*, **48**, 306 (1935).
21. E. Lyman, *Phys. Rev.*, **55**, 1123 (1939).
22. J. R. Richardson, *Phys. Rev.*, **55**, 609 (1939).
23. W. Fowler, L. Delsasso, and C. Lauritsen, *Phys. Rev.*, **49**, 561 (1936).
24. G. Seaborg and J. Hamilton, *Science*, **102**, 556 (1945).
25. E. McMillan and M. S. Livingston, *Phys. Rev.*, **47**, 452 (1935).
26. E. Amaldi, O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti, and E. Segré, *Proc. Roy. Soc.*, **149**, 522 (1935).
27. H. Newsom, *Phys. Rev.*, **48**, 790 (1935); **51**, 624 (1937).
28. F. Kurie, J. Richardson, and H. Paxton, *Phys. Rev.*, **49**, 368 (1936).
29. L. DuBridge, S. Barnes, J. Buck, and C. Strain, *Phys. Rev.*, **53**, 447 (1938).
30. A. Snell, *Phys. Rev.*, **51**, 143 (1936); **49**, 555 (1936); **52**, 1007 (1937).
31. T. Yasaki and S. Watanabe, *Nature*, **140**, 787 (1938).
32. J. Bower and W. Burcham, *Proc. Roy. Soc.*, **173**, 379 (1940).
33. S. Curran and J. Strothers, *Proc. Camb. Phil. Soc.*, **36**, 252 (1940).
34. M. White, L. Delsasso, J. Fox, and E. Creutz, *Phys. Rev.*, **56**, 512 (1939).
35. E. Pollard and W. Watson, *Phys. Rev.*, **57**, 1082 (1940); **58**, 12 (1940).
36. E. Creutz, J. Fox, and R. Sutton, *Phys. Rev.*, **57**, 567 (1940).
37. J. Laslett, *Phys. Rev.*, **52**, 529 (1937).
38. C. Magnan, *Comptes Rendus*, **205**, 1147 (1937).
39. L. Elliott, M. Deutsch, and A. Roberts, *Phys. Rev.*, **61**, 99 (1942); **63**, 219, 321, 457 (1943); **64**, 321 (1943).
40. T. Siegbahn, *Nature*, **153**, 221 (1944).
41. C. Mandeville and H. Fulbright, *Phys. Rev.*, **64**, 265 (1943); **63**, 387 (1943).

42. O. Huber, O. Lienhard, P. Scherrer, and H. Waffler, *Helv. Phys. Act.*, **16**, 33, 226, 431 (1943).
43. J. Itoh, *Proc. Phys. Math. Soc.*, Japan, **23**, 605 (1941).
44. M. Henderson, *Phys. Rev.*, **48**, 855 (1935).
45. O. Frisch, *Nature*, **133**, 721 (1934).
46. J. Cork, J. Richardson, and F. Kurie, *Phys. Rev.*, **49**, 208 (1936).
47. H. Bethe and W. Henderson, *Phys. Rev.*, **56**, 1060 (1939).
48. L. King and D. Elliott, *Phys. Rev.*, **59**, 108 (1941); **60**, 489 (1941); **59**, 403 (1941).
49. M. White, E. Creutz, L. Delsasso, and R. Wilson, *Phys. Rev.*, **59**, 63 (1941).
50. W. Barkas, E. Creutz, L. Delsasso, R. Sutton, and M. White, *Phys. Rev.*, **58**, 194, 383 (1940).
51. M. Poole, J. Cork, and R. Thornton, *Phys. Rev.*, **52**, 239 (1937).
52. R. Sagane, *Phys. Rev.*, **50**, 1141 (1936); **53**, 212 (1938); **55**, 31 (1939).
53. E. Lyman, *Phys. Rev.*, **51**, 1 (1937).
54. W. Libby and D. Lee, *Phys. Rev.*, **55**, 245 (1939).
55. M. Kamen, *Phys. Rev.*, **60**, 537 (1941).
56. J. Hoag, *Phys. Rev.*, **57**, 937 (1940).
57. H. Brandt, *Zeits. f. Phys.*, **108**, 726 (1938).
58. L. Ridenour and M. Henderson, *Phys. Rev.*, **52**, 889 (1937).
59. D. Graham and H. Walke, *Phys. Rev.*, **60**, 909 (1941).
60. S. Van Voorhis, *Phys. Rev.*, **49**, 889 (1936); **50**, 895 (1936).
61. S. Curran, P. Dee, and J. Strothers, *Proc. Roy. Soc.*, **174**, 546 (1940); **172**, 72 (1939).
62. D. Elliott and L. King, *Phys. Rev.*, **59**, 403 (1941).
63. P. Weimer, J. Kurbatov, and M. Poole, *Phys. Rev.*, **60**, 469 (1941).
64. D. Hurst and H. Walke, *Phys. Rev.*, **51**, 1033 (1937).
65. A. Bramley and A. Brewer, *Phys. Rev.*, **53**, 502 (1938).
66. H. Walke, F. Thompson, and J. Holt, *Phys. Rev.*, **57**, 171, 177 (1940).
67. H. Walke, *Phys. Rev.*, **57**, 163 (1940); **52**, 400, 663, 777 (1937).
68. C. Hibdon, M. Poole, and J. Kurbatov, *Phys. Rev.*, **63**, 462 (1943).
69. C. Mandeville, *Phys. Rev.*, **62**, 555 (1942); **64**, 147 (1943).
70. J. Allen, M. Poole, J. Kurbatov, and L. Quill, *Phys. Rev.*, **60**, 425 (1941).
71. H. Walke, E. Williams, and G. Evans, *Proc. Roy. Soc.*, **171**, 360 (1939).
72. J. O'Connor, M. Poole, and J. Kurbatov, *Phys. Rev.*, **62**, 413 (1942).
73. T. Amaki, T. Timori, and A. Sugimoto, *Phys. Rev.*, **57**, 751 (1940).
74. J. Livingood and G. Seaborg, *Phys. Rev.*, **53**, 847, 765 (1938); **54**, 391, 88 (1938); **55**, 457, 667 (1939); **60**, 913 (1941).
75. A. Hemmendinger, *Phys. Rev.*, **55**, 604 (1939); **58**, 929 (1940).
76. M. Deutsch and L. Elliott, *Phys. Rev.*, **65**, 211 (1944); **62**, 558 (1942).
77. J. Livingood and G. Seaborg, *Phys. Rev.*, **54**, 51, 775 (1938); **55**, 1268 (1939).
78. M. Deutsch, J. Downing, L. Elliott, J. Irvine, and A. Roberts, *Phys. Rev.*, **62**, 3 (1942).
79. B. Darling, B. Curtis, and J. Cork, *Phys. Rev.*, **51**, 1010 (1937).
80. H. Jensen, *Phys. Rev.*, **60**, 430 (1941).
81. M. Plesset, *Phys. Rev.*, **62**, 181 (1942).
82. F. Heyn, *Physica*, **4**, 160, 1224 (1937).
83. L. Delsasso, L. Ridenour, R. Sherr, and M. White, *Phys. Rev.*, **55**, 113 (1939).
84. A. Tyler, *Phys. Rev.*, **56**, 125 (1939).
85. A. Townsend, *Proc. Roy. Soc.*, **175**, 48 (1940); **177**, 357 (1941).
86. W. Chang, M. Goldhaber, and R. Sagane, *Nature*, **139**, 962 (1937).
87. R. Sagane, G. Miyamoto, and M. Ikawa, *Phys. Rev.*, **59**, 904 (1941).
88. A. Helmholz, *Phys. Rev.*, **60**, 415, 160 (1941); **61**, 204 (1942); **62**, 301 (1942).
89. A. Guthrie, *Phys. Rev.*, **60**, 746 (1941).
90. J. Buck, *Phys. Rev.*, **54**, 1024 (1938).
91. L. Alvarez, *Phys. Rev.*, **54**, 486 (1938).
92. W. Mann, *Phys. Rev.*, **52**, 405 (1937); **54**, 649 (1938).
93. J. Cork, L. Hadley, and C. Kent, *Phys. Rev.*, **61**, 388 (1942).

94. G. Seaborg, J. Livingood, and G. Friedlander, *Phys. Rev.*, **59**, 320 (1941).
95. B. Curtis and J. Cork, *Phys. Rev.*, **53**, 681 (1938).
96. R. Sagane, S. Kojima, G. Miyamoto, and M. Ikawa, *Proc. Phys. Math.*, Japan, **21**, 660, 728 (1939); **22**, 174 (1940).
97. G. Weil, *Phys. Rev.*, **60**, 167 (1941); **62**, 229 (1942); **56**, 485 (1939).
98. C. Kent, J. Cork, and G. Wadey, *Phys. Rev.*, **61**, 389 (1942).
99. A. Langsdorf and E. Segré, *Phys. Rev.*, **57**, 105 (1940).
100. G. Valley and R. McCreary, *Phys. Rev.*, **56**, 863 (1939).
101. G. Valley, *Phys. Rev.*, **57**, 1058 (1940); **59**, 686, 836 (1941); **60**, 167 (1941).
102. M. Deutsch and A. Roberts, *Phys. Rev.*, **60**, 362 (1941).
103. F. Strassmann and O. Hahn, *Naturwiss.*, **28**, 817 (1940).
104. E. Creutz, L. Delsasso, R. Sutton, M. White, and W. Barkas, *Phys. Rev.*, **58**, 481 (1940).
105. E. Clancy, *Phys. Rev.*, **58**, 88 (1940); **59**, 686 (1941); **60**, 87 (1941).
106. O. Hahn and F. Strassmann, *Naturwiss.*, **27**, 451, 529 (1939); **28**, 54, 61, 543 (1940); **29**, 369 (1941); **31**, 249 (1943); **30**, 324 (1942).
107. J. Hancock and J. Butler, *Phys. Rev.*, **57**, 1088 (1940).
108. A. Helmholz, C. Pecher, and J. Stout, *Phys. Rev.*, **59**, 902 (1941).
109. Z. Ollano, *Nuovo Cimento*, **18**, 11 (1941).
110. G. Glasoe and J. Steigman, *Phys. Rev.*, **57**, 566 (1940); **58**, 1 (1940).
111. L. DuBridge and J. Marshall, *Phys. Rev.*, **56**, 706 (1939); **57**, 348 (1940); **58**, 7 (1940).
112. D. Stewart, *Phys. Rev.*, **56**, 629 (1939).
113. D. Stewart, J. Lawson, and J. Cork, *Phys. Rev.*, **52**, 901 (1937).
114. H. Gotte, *Naturwiss.*, **28**, 449 (1940); **29**, 496 (1941); **30**, 108 (1942).
115. R. Sagane, S. Kojima, G. Miyamoto, and M. Ikawa, *Phys. Rev.*, **54**, 543, 970 (1938); **57**, 750 (1940).
116. A. V. Grosse and F. Booth, *Phys. Rev.*, **57**, 664 (1940).
117. G. Seaborg and E. Segré, *Phys. Rev.*, **55**, 808 (1939).
118. W. Maurer and W. Ramm, *Zeits. f. Phys.*, **119**, 334, 602 (1942).
119. B. Cacciapuoti, *Phys. Rev.*, **55**, 110 (1939).
120. D. Ewing, R. Perry, and R. McCreary, *Phys. Rev.*, **55**, 1136 (1936).
121. H. Devries and J. Veldkamp, *Physica*, **5**, 249 (1938).
122. Y. Nishima, T. Yasaki, M. Kimura, and M. Ikawa, *Phys. Rev.*, **58**, 660 (1940); **59**, 323, 677 (1941).
123. H. Born and W. Seelmann-Eggebert, *Naturwiss.*, **29**, 194 (1941); **31**, 86, 201, 420 (1943).
124. O. Minakawa, *Phys. Rev.*, **60**, 689 (1941).
125. B. Pontecorvo, *Phys. Rev.*, **54**, 542 (1938).
126. J. Kraus and J. Cork, *Phys. Rev.*, **52**, 763 (1937).
127. T. Enns, *Phys. Rev.*, **56**, 872 (1939).
128. M. Poole, *Phys. Rev.*, **53**, 116 (1938).
129. L. Alvarez, A. Helmholz, and E. Nelson, *Phys. Rev.*, **57**, 660 (1940).
130. W. Bothe and W. Gentner, *Zeits. f. Phys.*, **112**, 45 (1939).
131. M. Deutsch, A. Roberts, and L. Elliott, *Phys. Rev.*, **61**, 389 (1942); **64**, 268 (1943).
132. J. Cork and J. Lawson, *Phys. Rev.*, **56**, 291 (1939).
133. M. Wiedenbeck, *Phys. Rev.*, **66**, 36 (1944).
134. S. Barnes, *Phys. Rev.*, **56**, 414 (1939).
135. R. Smith, *Phys. Rev.*, **61**, 389 (1942).
136. J. Lawson and J. Cork, *Phys. Rev.*, **52**, 531 (1937); **56**, 131 (1939); **57**, 356, 982 (1940); **58**, 580 (1940).
137. M. Goldhaber, R. Hill, and L. Szilard, *Phys. Rev.*, **55**, 47 (1939).
138. E. Hales and E. Jordan, *Phys. Rev.*, **62**, 553 (1942).
139. P. Abelson, *Phys. Rev.*, **56**, 1 (1939).
140. G. Seaborg, J. Livingood, and J. Kennedy, *Phys. Rev.*, **57**, 363 (1940).
141. C. Kent and J. Cork, *Phys. Rev.*, **62**, 297 (1942).
142. G. Tape and J. Cork, *Phys. Rev.*, **53**, 676 (1938); **56**, 965 (1939).

143. E. Segré and C. Wu, *Phys. Rev.*, **57**, 552 (1940); **58**, 926 (1940); **61**, 203 (1942).
144. J. Downing, M. Deutsch, and A. Roberts, *Phys. Rev.*, **61**, 389, 686 (1942).
145. W. V. Riezler, *Naturwiss.*, **31**, 326 (1943).
146. D. Kalbfell and R. Cooley, *Phys. Rev.*, **58**, 91 (1940).
147. J. Cork and G. Smith, *Phys. Rev.*, **60**, 480 (1941).
148. P. Weimer, M. Poole, and J. Kurbatov, *Phys. Rev.*, **60**, 469 (1941); **63**, 59, 67 (1943); **64**, 43 (1943).
149. M. Poole and J. Cork, *Phys. Rev.*, **51**, 1010 (1937).
150. I. Curie and P. Savitch, *Comptes Rendus*, **208**, 343 (1939).
151. M. Poole, L. Quill, and J. Kurbatov, *Phys. Rev.*, **53**, 437 (1938); **63**, 463 (1943); **61**, 106 (1942).
152. J. DeWire, M. Poole, and J. Kurbatov, *Phys. Rev.*, **61**, 544, 564 (1942); **63**, 463 (1943).
153. T. Wilkins and A. Dempster, *Phys. Rev.*, **54**, 315 (1938).
154. K. Fajans and A. Voigt, *Phys. Rev.*, **60**, 533, 619, 626 (1941); **58**, 177 (1940).
155. G. Hevesy and G. Levi, *Nature*, **136**, 103 (1935); **137**, 185 (1936).
156. W. Bothe, *Naturwiss.*, **31**, 551 (1943).
157. J. Marsh and S. Sugden, *Nature*, **136**, 102 (1935).
158. W. Libby, *Phys. Rev.*, **56**, 21 (1939).
159. A. Flammersfeld and J. Mattauch, *Naturwiss.*, **31**, 66 (1943).
160. W. Bothe and W. Gentner, *Naturwiss.*, **25**, 19 (1937).
161. O. Oldenberg, *Phys. Rev.*, **53**, 35 (1938).
162. V. Zumstein, J. Kurbatov, and M. Poole, *Phys. Rev.*, **63**, 59 (1943).
163. K. Fajans and W. Sullivan, *Phys. Rev.*, **58**, 276 (1940).
164. E. Creutz, W. Barkas, and N. Furman, *Phys. Rev.*, **58**, 1008 (1940).
165. G. Seaborg and G. Friedlander, *Phys. Rev.*, **59**, 400 (1941).
166. E. McMillan, M. Kamen, and S. Ruben, *Phys. Rev.*, **52**, 375 (1937).
167. J. Cork and R. Thornton, *Phys. Rev.*, **51**, 59 (1937).
168. J. Cork and E. O. Lawrence, *Phys. Rev.*, **49**, 788 (1936).
169. R. Sherr, K. Bainbridge, and H. Anderson, *Phys. Rev.*, **60**, 473 (1941).
170. J. Cork, J. Halpern, and H. Tatel, *Phys. Rev.*, **57**, 371 (1940); **58**, 201 (1940).
171. G. Friedlander and C. Wu, *Phys. Rev.*, **60**, 747 (1941); **63**, 227 (1943).
172. R. Krishnan and E. Nahum, *Proc. Camb., Phil. Soc.*, **37**, 422 (1941).
173. L. King, W. Henderson, and J. Risser, *Phys. Rev.*, **55**, 1118 (1939).
174. B. Sargent, *Can. J. Res.*, **17**, 82 (1939); *Phys. Rev.*, **54**, 232 (1938).
175. M. Curie and others, *Rev. Mod. Phys.*, **3**, 427 (1931).
176. J. Dunworth, *Nature*, **144**, 152 (1939).
177. N. Ward, *Proc. Roy. Soc.*, **181**, 183 (1942).
178. D. Corson, K. Mackenzie, and E. Segré, *Phys. Rev.*, **57**, 459, 1087 (1940); **58**, 672 (1940).
179. B. V. Karlik and T. Bernert, *Naturwiss.*, **31**, 298, 492 (1943).
180. M. Holloway and M. Livingston, *Phys. Rev.*, **54**, 18 (1938).
181. M. Perey and M. Lecoin, *Comptes Rendus*, **212**, 893 (1941).
182. M. Lecoin, *J. de Phys. et Rad.*, **9**, 81 (1938).
183. W. Lewis and B. Bowden, *Proc. Roy. Soc.*, **145**, 235 (1934).
184. A. Kovarik and N. Adams, *Phys. Rev.*, **54**, 413 (1938).
185. A. V. Grosse, E. Booth, and J. Dunning, *Phys. Rev.*, **56**, 382 (1939); **59**, 322 (1941).
186. A. V. Grosse, *J. Am. Chem. Soc.*, **52**, 1742 (1930).
187. A. O. Nier, *Phys. Rev.*, **55**, 150 (1939).
188. E. McMillan, *Phys. Rev.*, **58**, 178 (1940); **55**, 510 (1939).
189. J. Irvine, *Phys. Rev.*, **55**, 1105 (1939).
190. E. McMillan and P. Abelson, *Phys. Rev.*, **57**, 1185 (1940).
191. G. T. Seaborg, Private Communication.
192. P. G. Kruger and W. G. Ogle, *Phys. Rev.*, **67**, 273 (1945).
193. J. L. Lawson and J. M. Cork, *Phys. Rev.*, **58**, 580 (1940).
194. Isotope Committee, *Science*, **103**, 697 (1946).

# APPENDIX

## TABLE A I. FUNDAMENTAL CONSTANTS

### *Electronic*[1]

Charge of electron $(4.8021 \pm 0.0006) \times 10^{-10}$ esu.
$(1.60203 \pm 0.00034) \times 10^{-20}$ emu.
Specific charge of electron $\left(\frac{e}{m_0}\right)$ $(1.7592 \pm 0.0005) \times 10^{7}$ emu per gm.
Atomic weight of electron (Aston) 0.0005486.
Mass of electron $(9.1066 \pm 0.0032) \times 10^{-28}$ gm.
1 ampere $= 6.242 \times 10^{18}$ electrons per sec.

### *Atomic*[1]

Mass of hydrogen atom $(1.67339 \pm 0.00031) \times 10^{-24}$ gm.
Mass of atom of unit atomic weight $(1.66035 \pm 0.00031) \times 10^{-24}$ gm.
Avogadro's number $(6.02338 \pm 0.00043) \times 10^{23}$ per gm. mol.
Loschmidt's number (NPT) $(2.6870 \pm 0.0005) \times 10^{19}$ per cm$^3$.
Volume 1 gm. mol. gas (NPT) $(22{,}414 \pm 0.8)$ cm$^3$.
Boltzmann's gas constant $(1.3708 \pm 0.0014) \times 10^{-16}$ erg per deg. C. per particle.
Specific charge of proton $(e/m)$ $(9578.8 \pm 1.0)$ emu per gm.
Specific charge of alpha particle $(e/m)$ $(4822.3 \pm 0.5)$ emu per gm.

### *Radiation*

Planck constant $(h)$, $6.624 \pm 0.002 \times 10^{-27}$ erg sec.
Solar constant $1.353 \times 10^{6}$ ergs per cm$^2$ per sec.
Velocity of radiation (vacuum, $2.99776 \pm 0.00004) \times 10^{10}$ cm per sec.
Curie of radioactive material: $37.1 \times 10^{9}$ disintegrations per sec.

### *Energy Transformations*

1 Mev $= 1.07 \times 10^{-3}$ mass units $= 1.6 \times 10^{-6}$ ergs $= 4.45 \times 10^{-20}$ KWH.
1 mass unit $= 931$ Mev $= 1.49 \times 10^{-3}$ ergs $= 4.15 \times 10^{-17}$ KWH.
1 erg $= 671$ mass units $= 6.24 \times 10^{5}$ Mev $= 2.78 \times 10^{-14}$ KWH.
1 KWH $= 2.41 \times 10^{16}$ mass units $= 2.25 \times 10^{19}$ Mev $= 3.60 \times 10^{3}$ ergs.
1 gm. $(mc^2) = 9 \times 10^{20}$ ergs $= 25.02 \times 10^{6}$ KWH.

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[1] R. T. Birge, *Phys. Rev.*, **63**, 213 (1943); *Rev. Mod. Phys.*, **13**, 233 (1941); *Amer. Jour. Phys.*, **13**, 63 (1945).

### TABLE A II. USEFUL INFORMATION CONCERNING ELECTRONS

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*Equations*

The energy $W$, from relativity, is:

1. $W = mc^2 - m_oc^2 = m_oc^2\left[\frac{1}{\sqrt{1-\beta^2}} - 1\right] = m_oc^2\left[\frac{1}{2}\beta^2 + \frac{3}{8}\beta^4 + \frac{5}{16}\beta^6 + \ldots\right]$
$= \frac{1}{2}m_ov^2\left[1 + \frac{3}{4}\beta^2 + \frac{5}{8}\beta^4 + \ldots\right]$ ergs, where $m$ is the mass and $m_o$ the rest mass of the electron and $\beta$ is the ratio of its velocity $v$ to that of light $c$.

The ratio of the mass $m$ to the rest mass $m_o$ from equation 1 is:

2. $\frac{m}{m_o} = \frac{W}{m_oc^2} + 1 = \frac{W(\text{Mev})}{0.51} + 1.$

The momentum, $P = Mv$, from equation 1 is:

3. $P = mv = \frac{1}{c}\sqrt{W(W + 2m_oc^2)}$ (gm. cm per sec.).

The radius $\rho$ of the circular path in a field of $B$ Gauss is:

4. $\text{Bev} = \frac{mv^2}{\rho}$, or $B\rho = \frac{mv}{e(\text{emu})}$ (Gauss-cm).

5. $B\rho = \frac{1}{ce}\sqrt{W(W + 2m_oc^2)} = \frac{10^4}{3}\sqrt{W'(W' + 1.02)}$ where $W'$ is in Mev.

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TABLE A III. DATA ON ELECTRONS

| *β* | *W* (*Kev*) | *Bρ* | *m*/*m*₀ | *β* | *W* (*Kev*) | *Bρ* | *m*/*m*₀ |
|---|---|---|---|---|---|---|---|
| 0.00198 | 0.001 | 3.37 | 1.00000 | 0.22 | 12.83 | 384.2 | 1.02512 |
| 0.00280 | 0.002 | 4.76 | 1.00000 | 0.23 | 14.07 | 402.6 | 1.02755 |
| 0.00343 | 0.003 | 5.84 | 1.00000 | 0.24 | 15.38 | 421.3 | 1.03011 |
| 0.00396 | 0.004 | 6.74 | 1.00000 | 0.25 | 16.75 | 440.0 | 1.03280 |
| 0.00443 | 0.005 | 7.53 | 1.00001 | 0.26 | 18.18 | 458.8 | 1.0356 |
| 0.00485 | 0.006 | 8.25 | 1.00001 | 0.27 | 19.69 | 477.8 | 1.0385 |
| 0.005 | 0.00638 | 8.50 | 1.00001 | 0.28 | 21.28 | 496.8 | 1.0416 |
| 0.00524 | 0.007 | 8.91 | 1.00001 | 0.29 | 22.94 | 516.2 | 1.0449 |
| 0.00560 | 0.008 | 9.53 | 1.00001 | 0.30 | 24.66 | 535.9 | 1.0482 |
| 0.00594 | 0.009 | 10.10 | 1.00001 | 0.31 | 26.47 | 555.7 | 1.0518 |
| 0.00626 | 0.010 | 10.65 | 1.00002 | 0.32 | 28.36 | 575.3 | 1.0555 |
| 0.00886 | 0.020 | 15.06 | 1.00004 | 0.33 | 30.31 | 595.6 | 1.0593 |
| 0.0100 | 0.02554 | 17.0 | 1.00005 | 0.34 | 32.37 | 616.0 | 1.0633 |
| 0.0109 | 0.030 | 18.45 | 1.00006 | 0.35 | 34.49 | 636.6 | 1.0675 |
| 0.0125 | 0.040 | 21.3 | 1.00008 | 0.36 | 36.70 | 657.5 | 1.0718 |
| 0.0140 | 0.050 | 24.6 | 1.00010 | 0.37 | 39.01 | 678.7 | 1.0763 |
| 0.0198 | 0.100 | 33.7 | 1.00019 | 0.38 | 41.42 | 700.0 | 1.0811 |
| 0.0200 | 0.1022 | 34.06 | 1.00020 | 0.39 | 43.92 | 721.5 | 1.0860 |
| 0.0280 | 0.200 | 47.6 | 1.00039 | 0.40 | 46.53 | 743.5 | 1.0910 |
| 0.0300 | 0.230 | 51.04 | 1.00045 | 0.41 | 49.23 | 766.0 | 1.0963 |
| 0.0343 | 0.300 | 58.3 | 1.00059 | 0.414 | 50.00 | 775.0 | 1.0983 |
| 0.0400 | 0.4087 | 68.1 | 1.00080 | 0.42 | 52.05 | 788.3 | 1.1019 |
| 0.0442 | 0.500 | 75.3 | 1.00098 | 0.43 | 54.97 | 811.4 | 1.1076 |
| 0.0500 | 0.6385 | 85.0 | 1.00125 | 0.44 | 58.03 | 834.9 | 1.1135 |
| 0.0560 | 0.800 | 95.2 | 1.00157 | 0.45 | 61.19 | 858.6 | 1.1197 |
| 0.060 | 0.9248 | 102.3 | 1.00181 | 0.46 | 64.50 | 882.5 | 1.1262 |
| 0.0626 | 1.00 | 106.6 | 1.00196 | 0.47 | 67.91 | 907.3 | 1.1329 |
| 0.07 | 1.257 | 119.6 | 1.00246 | 0.48 | 71.43 | 932.2 | 1.1399 |
| 0.08 | 1.644 | 136.7 | 1.00322 | 0.49 | 75.17 | 957.6 | 1.1471 |
| 0.0883 | 2.000 | 151.0 | 1.00391 | 0.50 | 79.03 | 983.6 | 1.1547 |
| 0.09 | 2.083 | 154.0 | 1.00408 | 0.51 | 83.04 | 1010. | 1.1625 |
| 0.10 | 2.575 | 171.3 | 1.00504 | 0.52 | 87.20 | 1038. | 1.1707 |
| 0.11 | 3.122 | 188.5 | 1.00611 | 0.53 | 91.57 | 1065. | 1.1792 |
| 0.12 | 3.720 | 205.9 | 1.00728 | 0.54 | 96.08 | 1093. | 1.1881 |
| 0.124 | 4.000 | 214.0 | 1.00783 | 0.548 | 100.0 | 1116. | 1.1955 |
| 0.13 | 4.373 | 223.4 | 1.00856 | 0.55 | 100.8 | 1122. | 1.1973 |
| 0.138 | 5.00 | 239.0 | 1.00967 | 0.56 | 105.8 | 1151. | 1.2070 |
| 0.14 | 5.083 | 241.0 | 1.00995 | 0.57 | 110.9 | 1182. | 1.2170 |
| 0.15 | 5.844 | 258.4 | 1.01144 | 0.58 | 116.2 | 1214. | 1.2275 |
| 0.16 | 6.668 | 276.1 | 1.01305 | 0.59 | 121.9 | 1245. | 1.2385 |
| 0.17 | 7.546 | 293.9 | 1.01477 | 0.60 | 127.7 | 1278. | 1.2500 |
| 0.18 | 8.479 | 311.9 | 1.01660 | 0.61 | 133.8 | 1312. | 1.2619 |
| 0.19 | 9.478 | 329.7 | 1.01855 | 0.62 | 140.2 | 1346. | 1.2745 |
| 0.195 | 10.00 | 340.0 | 1.01958 | 0.63 | 147.0 | 1382. | 1.2876 |
| 0.20 | 10.53 | 347.8 | 1.02062 | 0.64 | 154.1 | 1420. | 1.3014 |
| 0.21 | 11.66 | 366.0 | 1.02281 | 0.65 | 161.3 | 1458. | 1.3159 |

TABLE A III. DATA ON ELECTRONS (*Continued*)

| $\beta$ | $W$ (*Kev*) | $B\rho$ | $m/m_0$ | $\beta$ | $W$ (*Kev*) | $B\rho$ | $m/m_0$ |
|---|---|---|---|---|---|---|---|
| 0.66 | 169.2 | 1497. | 1.3310 | 0.938 | 962.8 | 4610. | 2.8848 |
| 0.67 | 177.2 | 1538. | 1.3470 | 0.940 | 986.4 | 4694. | 2.9310 |
| 0.68 | 185.8 | 1580. | 1.3638 | 0.9411 | 1000. | 4739. | 2.9577 |
| 0.69 | 194.9 | 1623. | 1.3815 | 0.942 | 1010. | 4782. | 2.9796 |
| 0.695 | 200.0 | 1646. | 1.3920 | 0.944 | 1038. | 4874. | 3.0308 |
| 0.70 | 204.3 | 1669. | 1.4002 | 0.946 | 1065. | 4971. | 3.0848 |
| 0.71 | 214.4 | 1718. | 1.4200 | 0.948 | 1094. | 5074. | 3.1419 |
| 0.72 | 225.3 | 1768. | 1.4409 | 0.95 | 1125. | 5183. | 3.2025 |
| 0.73 | 236.4 | 1820. | 1.4631 | 0.952 | 1158. | 5299. | 3.2669 |
| 0.74 | 248.5 | 1874. | 1.4867 | 0.954 | 1192. | 5420. | 3.3354 |
| 0.75 | 261.4 | 1933. | 1.5118 | 0.956 | 1231. | 5551. | 3.4087 |
| 0.76 | 275.2 | 1992. | 1.5386 | 0.958 | 1271. | 5691. | 3.4871 |
| 0.77 | 289.7 | 2056. | 1.5672 | 0.960 | 1313. | 5841. | 3.5714 |
| 0.78 | 305.6 | 2124. | 1.5980 | 0.962 | 1360. | 6002. | 3.6623 |
| 0.79 | 322.3 | 2195. | 1.6310 | 0.964 | 1411. | 6178. | 3.7607 |
| 0.80 | 340.5 | 2272. | 1.6666 | 0.966 | 1465. | 6365. | 3.8678 |
| 0.81 | 360.2 | 2354. | 1.7052 | 0.968 | 1525. | 6573. | 3.9848 |
| 0.82 | 381.8 | 2441. | 1.7471 | 0.970 | 1591. | 6796. | 4.1134 |
| 0.83 | 405.0 | 2536. | 1.7928 | 0.972 | 1662. | 7048. | 4.2556 |
| 0.84 | 430.7 | 2638. | 1.8430 | 0.974 | 1743. | 7324. | 4.4140 |
| 0.85 | 458.9 | 2749. | 1.8983 | 0.976 | 1834. | 7637. | 4.5919 |
| 0.86 | 490.3 | 2870. | 1.9596 | 0.978 | 1938. | 7990. | 4.7937 |
| 0.863 | 500.0 | 2925. | 1.9907 | 0.980 | 2057. | 8391. | 5.0252 |
| 0.87 | 525.3 | 3006. | 2.0281 | 0.982 | 2194. | 8869. | 5.2943 |
| 0.88 | 564.6 | 3156. | 2.1053 | 0.984 | 2356. | 9410. | 5.6126 |
| 0.89 | 609.6 | 3325. | 2.1931 | 0.986 | 2553. | 10,080. | 5.9971 |
| 0.90 | 661.1 | 3517. | 2.2941 | 0.988 | 2796. | 10,890. | 6.4744 |
| 0.902 | 671.2 | 3559. | 2.3162 | 0.990 | 3110. | 11,960. | 7.0888 |
| 0.904 | 684.1 | 3601. | 2.3390 | 0.991 | 3305. | 12,620. | 7.4703 |
| 0.906 | 695.0 | 3646. | 2.3625 | 0.992 | 3536. | 13,380. | 7.9215 |
| 0.908 | 708.3 | 3693. | 2.3868 | 0.993 | 3814. | 14,320. | 8.4664 |
| 0.910 | 721.3 | 3740. | 2.4119 | 0.994 | 4160. | 15,480. | 9.1424 |
| 0.912 | 734.5 | 3788. | 2.4379 | 0.9950 | 4604. | 16,980. | 10.0125 |
| 0.914 | 748.2 | 3838. | 2.4647 | 0.9955 | 4881. | 17,900. | 10.5528 |
| 0.916 | 762.4 | 3891. | 2.4926 | 0.9960 | 5206. | 18,990. | 11.1915 |
| 0.918 | 777.3 | 3942. | 2.5215 | 0.9965 | 5600. | 20,310. | 11.9628 |
| 0.92 | 792.5 | 3990. | 2.5515 | 0.9970 | 6090. | 21,950. | 12.9196 |
| 0.922 | 808.5 | 4058. | 2.5827 | 0.9975 | 6718. | 24,050. | 14.1510 |
| 0.924 | 825.0 | 4118. | 2.6151 | 0.9980 | 7571. | 26,900. | 15.8193 |
| 0.926 | 842.2 | 4179. | 2.6488 | 0.9985 | 8119. | 31,070. | 18.2643 |
| 0.928 | 860.0 | 4244. | 2.6839 | 0.9990 | 10,900. | 38,080. | 22.3663 |
| 0.930 | 879.1 | 4311. | 2.7206 | 0.9995 | 15,630. | 53,860. | 31.6268 |
| 0.932 | 898.5 | 4381. | 2.7589 | $0.9_4$—871 | $10^5$ | $3.349 \times 10^5$ | 196.77 |
| 0.934 | 918.9 | 4454. | 2.7989 | $0.9_6$—870 | $10^6$ | $3.33 \times 10^6$ | 1958.7 |
| 0.936 | 940.3 | 4531. | 2.8409 | $0.9_7$—870 | $10^7$ | $3.33 \times 10^7$ | 19,587. |

TABLE A IV. USEFUL INFORMATION REGARDING PROTONS IN MOTION

| *V (Cm/sec)* | *β (V/C)* | *W (Kev)* | *Bρ (Gauss-Cm)* | *Range (Cm Air)* |
|---|---|---|---|---|
| $1.0 \times 10^9$ | 0.03333 | 522 | $1.044 \times 10^5$ | 0.8 |
| 1.1 | 0.03666 | 632 | 1.149 | 1.1 |
| 1.2 | 0.04000 | 753 | 1.253 | 1.4 |
| 1.3 | 0.04333 | 884 | 1.358 | 1.8 |
| 1.4 | 0.046666 | 1,025 | 1.463 | 2.3 |
| 1.5 | 0.05000 | 1,177 | 1.568 | 2.9 |
| 1.6 | 0.05333 | 1,340 | 1.673 | 3.6 |
| 1.7 | 0.05666 | 1,513 | 1.778 | 4.4 |
| 1.8 | 0.06000 | 1,697 | 1.883 | 5.3 |
| 1.9 | 0.06333 | 1,891 | 1.988 | 6.3 |
| 2.0 | 0.06666 | 2,095 | 2.093 | 7.5 |
| 2.1 | 0.07000 | 2,310 | 2.198 | 8.9 |
| 2.2 | 0.07333 | 2,536 | 2.304 | 10.4 |
| 2.3 | 0.07666 | 2,773 | 2.409 | 12.1 |
| 2.4 | 0.08000 | 3,021 | 2.514 | 14.0 |
| 2.5 | 0.08333 | 3,280 | 2.619 | 16.1 |
| 2.6 | 0.08666 | 3,649 | 2.725 | 18.4 |
| 2.7 | 0.09000 | 3,929 | 2.830 | 21.0 |
| 2.8 | 0.09333 | 4,120 | 2.936 | 23.9 |
| 2.9 | 0.09666 | 4,422 | 3.042 | 27.0 |
| 3.0 | 0.10000 | 4,734 | 3.148 | 30.4 |
| 3.1 | 0.10333 | 5,057 | 3.254 | 34.1 |
| 3.2 | 0.10666 | 5,391 | 3.360 | 38.2 |
| 3.3 | 0.11000 | 5,736 | 3.467 | 42.6 |
| 3.4 | 0.11333 | 6,092 | 3.573 | 47.4 |
| 3.5 | 0.11666 | 6,460 | 3.680 | 52.6 |
| 3.6 | 0.12000 | 6,838 | 3.786 | 58.2 |
| 3.7 | 0.12333 | 7,227 | 3.893 | 64.1 |
| 3.8 | 0.12666 | 7,628 | 4.000 | 70.5 |
| 3.9 | 0.13000 | 8,040 | 4.107 | 77.4 |
| 4.0 | 0.13333 | 8,463 | 4.214 | 84.8 |
| 4.1 | 0.13666 | 8,897 | 4.321 | 92.7 |
| 4.2 | 0.14000 | 9,343 | 4.428 | 101.3 |
| 4.3 | 0.14333 | 9,800 | 4.535 | 110.4 |
| 4.4 | 0.14666 | 10,270 | 4.643 | 119.9 |
| 4.5 | 0.15000 | 10,750 | 4.750 | 130.0 |
| 4.6 | 0.15333 | 11,240 | 4.858 | 140.8 |
| 4.7 | 0.15666 | 11,740 | 4.966 | 152.3 |
| 4.8 | 0.16000 | 12,250 | 5.075 | 164.6 |
| 4.9 | 0.16333 | 12,770 | 5.184 | 177.5 |
| 5.0 | 0.16666 | 13,310 | 5.293 | 191.1 |

*Note:*—A deuteron whose range is twice the range of a proton possesses twice the energy, hence Table A IV may be used equally well for the range of deuterons up to 26.6 Mev.

TABLE A V. USEFUL INFORMATION REGARDING ALPHA PARTICLES

| *V* (*Cm/sec*) | $\beta$ (*V/C*) | *W* (*Kev*) | *Bρ* (*Gauss-Cm*) | *Range* (*Cm Air*) | *Ion Pairs* |
|---|---|---|---|---|---|
| $0.75 \times 10^9$ | 0.0250 | 1,167 | $1.5555 \times 10^5$ | 0.55 | $0.33 \times 10^5$ |
| 0.80 | 0.266 | 1,328 | 1.6593 | 0.62 | 0.38 |
| 0.85 | 0.02833 | 1,499 | 1.7631 | 0.70 | 0.43 |
| 0.90 | 0.03000 | 1,681 | 1.8669 | 0.80 | 0.48 |
| 0.95 | 0.03166 | 1,873 | 1.9707 | 0.91 | 0.53 |
| 1.00 | 0.03333 | 2,075 | 2.0745 | 1.04 | 0.59 |
| 1.05 | 0.03500 | 2,288 | 2.1783 | 1.18 | 0.65 |
| 1.10 | 0.03666 | 2,511 | 2.2822 | 1.32 | 0.72 |
| 1.15 | 0.03833 | 2,745 | 2.3862 | 1.48 | 0.79 |
| 1.20 | 0.04000 | 2,989 | 2.4901 | 1.67 | 0.86 |
| 1.25 | 0.04166 | 3,244 | 2.5941 | 1.87 | 0.93 |
| 1.30 | 0.04333 | 3,509 | 2.6980 | 2.09 | 1.00 |
| 1.35 | 0.04500 | 3,785 | 2.8019 | 2.33 | 1.08 |
| 1.40 | 0.04666 | 4,071 | 2.9060 | 2.58 | 1.17 |
| 1.45 | 0.04833 | 4,368 | 3.0100 | 2.864 | 1.25 |
| 1.50 | 0.05000 | 4,674 | 3.1141 | 3.169 | 1.34 |
| 1.55 | 0.05166 | 4,991 | 3.2181 | 3.499 | 1.43 |
| 1.60 | 0.05333 | 5,319 | 3.3221 | 3.853 | 1.52 |
| 1.65 | 0.05500 | 5,658 | 3.4263 | 4.240 | 1.62 |
| 1.70 | 0.05666 | 6,008 | 3.5304 | 4.652 | 1.72 |
| 1.75 | 0.05833 | 6,367 | 3.6346 | 5.093 | 1.82 |
| 1.80 | 0.06000 | 6,737 | 3.7388 | 5.569 | 1.93 |
| 1.85 | 0.06166 | 7,117 | 3.8431 | 6.079 | 2.03 |
| 1.90 | 0.06333 | 7,508 | 3.9474 | 6.621 | 2.15 |
| 1.95 | 0.06500 | 7,910 | 4.0517 | 7.202 | 2.26 |
| 2.00 | 0.06666 | 8,322 | 4.1560 | 7.821 | 2.38 |
| 2.05 | 0.06833 | 8,745 | 4.2604 | 8.479 | 2.50 |
| 2.10 | 0.07000 | 9,178 | 4.3648 | 9.177 | 2.62 |
| 2.15 | 0.07166 | 9,622 | 4.4693 | 9.919 | 2.76 |
| 2.20 | 0.07333 | 10,077 | 4.5739 | 10.706 | 2.88 |
| 2.25 | 0.07500 | 10,543 | 4.6784 | 11.536 | 3.02 |
| 2.30 | 0.07666 | 11,018 | 4.7830 | 12.416 | 3.16 |
| 2.35 | 0.07833 | 11,504 | 4.8876 | 13.433 | 3.29 |
| 2.40 | 0.08000 | 12,001 | 4.9922 | 14.322 | 3.44 |
| 2.45 | 0.08166 | 12,508 | 5.1369 | 15.353 | 3.58 |
| 2.50 | 0.08333 | 13,027 | 5.2016 | 16.441 | 3.73 |

TABLE A VI. EXCITATION POTENTIALS FOR THE ELEMENTS, IN KILOVOLTS

| *Element* | *K* | *L* | *M* | *N* | *Element* | *K* | *L* | *M* | *N* |
|---|---|---|---|---|---|---|---|---|---|
| 92 U | 115 | 21.7 | 5.54 | 1.44 | 52 Te | 31.8 | 4.93 | 1.01 | 0.17 |
| 90 Th | 109 | 20.5 | 5.17 | 1.33 | 51 Sb | 30.4 | 4.69 | 0.94 | 0.15 |
| 82 Pb | 87.6 | 15.8 | 3.85 | 0.89 | 50 Sn | 29.1 | 4.49 | 0.88 | 0.13 |
| 81 Tl | 85.2 | 15.3 | 3.71 | 0.86 | 49 In | 27.9 | 4.28 | 0.83 | 0.12 |
| 80 Hg | 82.9 | 14.8 | 3.57 | 0.82 | 48 Cd | 26.7 | 4.07 | 0.77 | 0.11 |
| 79 Au | 80.5 | 14.4 | 3.43 | 0.79 | 47 Ag | 25.5 | 3.79 | 0.72 | 0.10 |
| 78 Pt | 78.1 | 13.9 | 3.30 | 0.71 | 46 Pd | 24.4 | 3.64 | 0.67 | 0.08 |
| 77 Ir | 76.0 | 13.4 | 3.17 | 0.67 | 45 Rh | 23.2 | 3.43 | 0.62 | 0.07 |
| 76 Os | 73.8 | 13.0 | 3.05 | 0.64 | 44 Ru | 22.1 | 3.24 | 0.59 | 0.06 |
| 74 W | 69.3 | 12.1 | 2.81 | 0.59 | 42 Mo | 20.0 | 2.87 | 0.51 | 0.06 |
| 73 Ta | 67.4 | 11.7 | 2.71 | 0.57 | 41 Nb | 19.0 | 2.68 | 0.48 | 0.05 |
| 72 Hf | 65.4 | 11.3 | 2.60 | 0.54 | 40 Zr | 18.0 | 2.51 | 0.43 | 0.05 |
| 71 Lu | 63.4 | 10.9 | 2.50 | 0.51 | 39 Y | 17.0 | 2.36 |  |  |
| 70 Yb | 61.4 | 10.5 | 2.41 | 0.50 | 38 Sr | 16.1 | 2.19 |  |  |
| 69 Tm | 59.5 | 10.1 | 2.31 | 0.47 | 37 Rb | 15.2 | 2.05 |  |  |
| 68 Er | 57.5 | 9.73 | 2.22 | 0.45 | 36 Kr | 14.3 | 1.91 |  |  |
| 67 Ho | 55.8 | 9.38 | 2.13 | 0.43 | 35 Br | 13.5 | 1.77 |  |  |
| 66 Dy | 53.8 | 9.03 | 2.04 | 0.42 | 34 Se | 12.7 | 1.64 |  |  |
| 65 Tb | 52.0 | 8.70 | 1.96 | 0.40 | 33 As | 11.9 | 1.52 |  |  |
| 64 Gd | 50.3 | 8.37 | 1.88 | 0.38 | 32 Ge | 11.1 | 1.41 |  |  |
| 63 Eu | 48.6 | 8.04 | 1.80 | 0.36 | 31 Ga | 10.4 | 1.31 |  |  |
| 62 Sm | 46.8 | 7.73 | 1.72 | 0.35 | 30 Zn | 9.65 | 1.20 |  |  |
| 60 Nd | 43.6 | 7.12 | 1.58 | 0.32 | 29 Cu | 8.86 |  |  |  |
| 59 Pr | 41.9 | 6.83 | 1.51 | 0.30 | 28 Ni | 8.29 |  |  |  |
| 58 Ce | 40.3 | 6.54 | 1.43 | 0.29 | 27 Co | 7.71 |  |  |  |
| 57 La | 38.7 | 6.26 | 1.36 | 0.27 | 26 Fe | 7.10 |  |  |  |
| 56 Ba | 37.4 | 5.99 | 1.29 | 0.25 | 25 Mn | 6.54 |  |  |  |
| 55 Cs | 35.9 | 5.71 | 1.21 | 0.23 | 24 Cr | 5.98 |  |  |  |
| 54 Xe | 34.5 | 5.44 | 1.14 | 0.21 | 23 Va | 5.45 |  |  |  |
| 53 I | 33.2 | 5.18 | 1.08 | 0.19 | 22 Ti | 4.95 |  |  |  |

TABLE A VII. RANGE OF HIGH ENERGY PROTONS

(A deuteron with twice the energy of a proton will have twice the range.)

| *Energy in Mev* | *Range in Cm of Al* | *Range in Meters of Air* |
|---|---|---|
| 10,000 | 2038.0 | 41,080.0 |
| 9,000 | 1841.0 | 37,100.0 |
| 8,000 | 1642.0 | 33,060.0 |
| 7,000 | 1440.0 | 28,950.0 |
| 6,000 | 1234.0 | 24,790.0 |
| 5,000 | 1024.0 | 20,540.0 |
| 4,000 | 809.0 | 16,220.0 |
| 3,000 | 590.6 | 11,810.0 |
| 2,000 | 368.3 | 7,344.0 |
| 1,000 | 150.2 | 2,982.0 |
| 900 | 129.7 | 2,572.0 |
| 800 | 109.7 | 2,174.0 |
| 700 | 90.33 | 1,788.0 |
| 600 | 71.80 | 1,420.0 |
| 500 | 54.35 | 1,073.0 |
| 400 | 38.27 | 754.4 |
| 300 | 24.01 | 472.1 |
| 200 | 12.17 | 238.3 |
| 100 | 3.651 | 70.95 |
| 90 | 3.031 | 58.83 |
| 80 | 2.461 | 47.69 |
| 70 | 1.941 | 37.56 |
| 60 | 1.476 | 28.49 |
| 50 | 1.069 | 20.53 |
| 40 | .7162 | 13.74 |
| 30 | .4287 | 8.194 |
| 15 | .1257 | 2.385 |

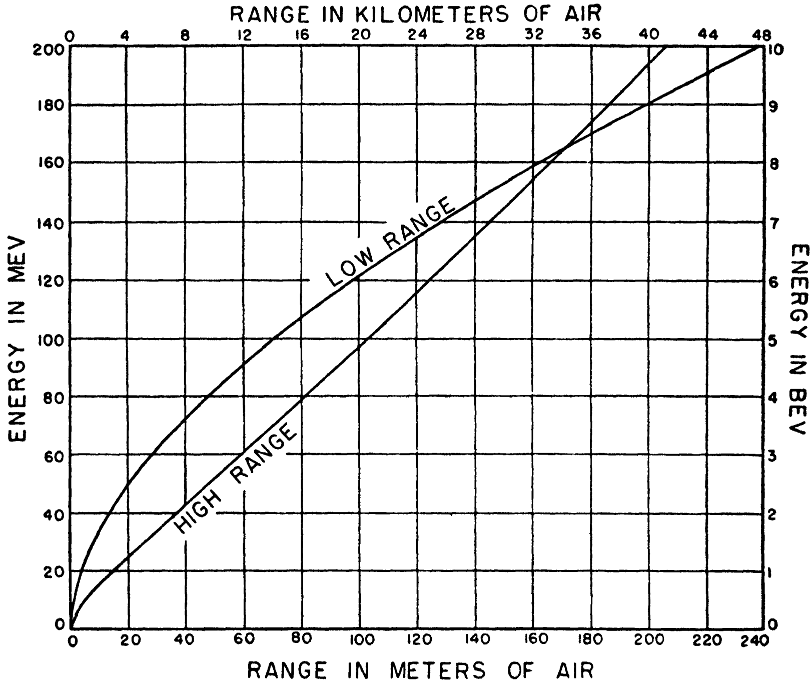

FIG. A.1. Range of energetic protons in air. (From calculations by J. H. Smith and H. A. Bethe.)

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